

# Synthetic electromagnetism with neutral atoms

I. B. Spielman

## **Floquet topology**

G. H. Reid, A. Pineiro, A. Fritsch, and  
M. Lu, **with Justyna Zwolak**

## **Synthetic Hall cylinder**

M. Zhao, J. Tao, and Q. Liang

## **SOC, disorder, and weak measurement:**

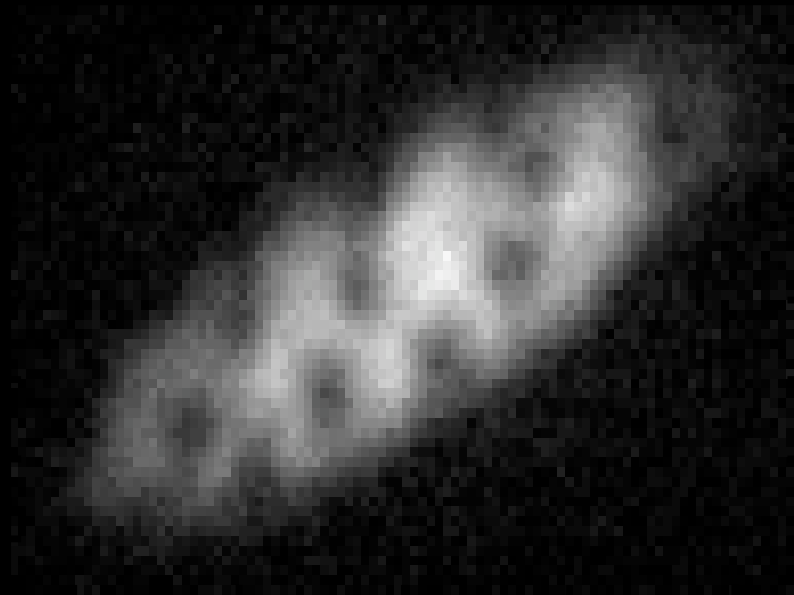
E. Altuntas



## **Support**

**NSF PFC@JQI, AFOSR Quantum Phases MURI, and NIST**

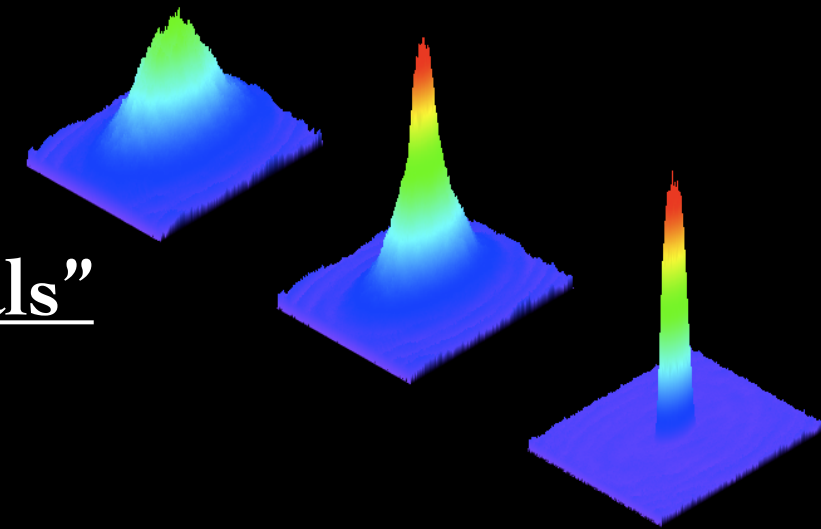
# Ultracold neutral atoms as a material system



## Cold atoms are good “materials”

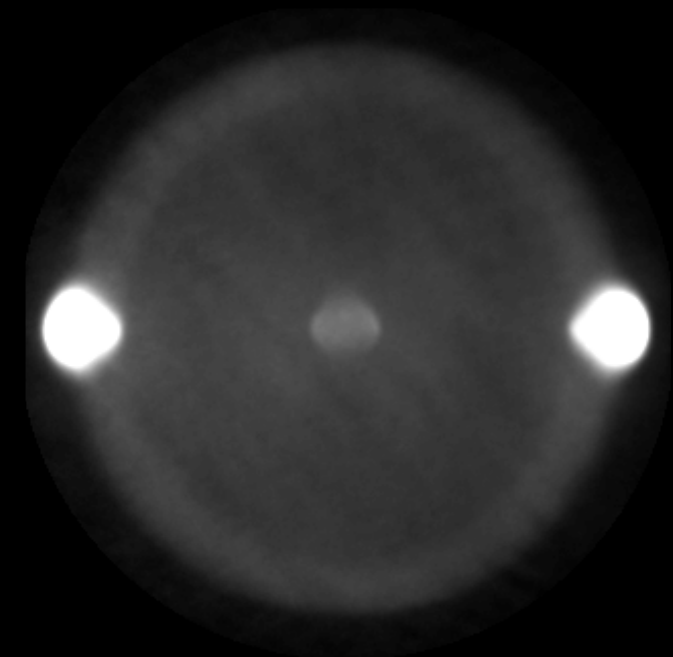
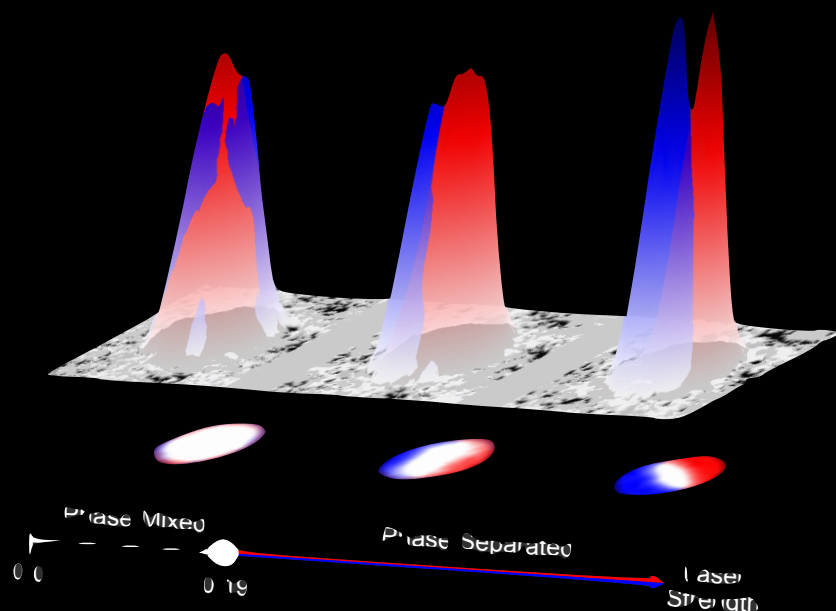
Numerous properties can  
be controlled and measured  
on all relevant timescales and  
in any lab

Very simple Hamiltonians



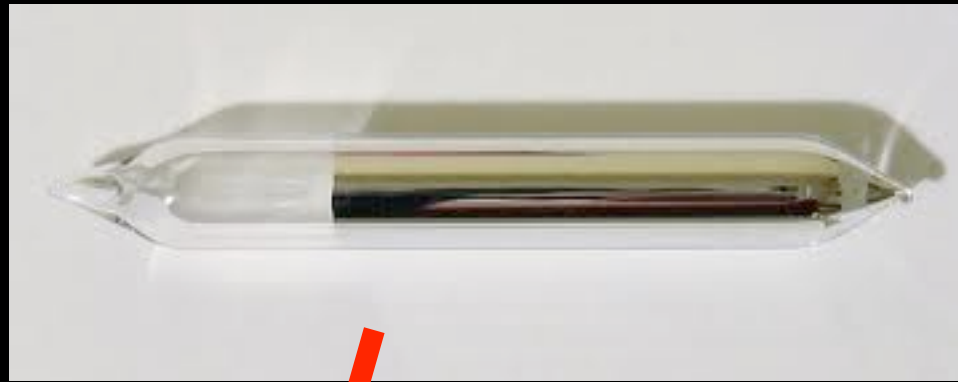
## Cold atoms are bad “materials” Short lived, and do so in vacuum

Interesting features **all** added  
by hand (complex experiments).



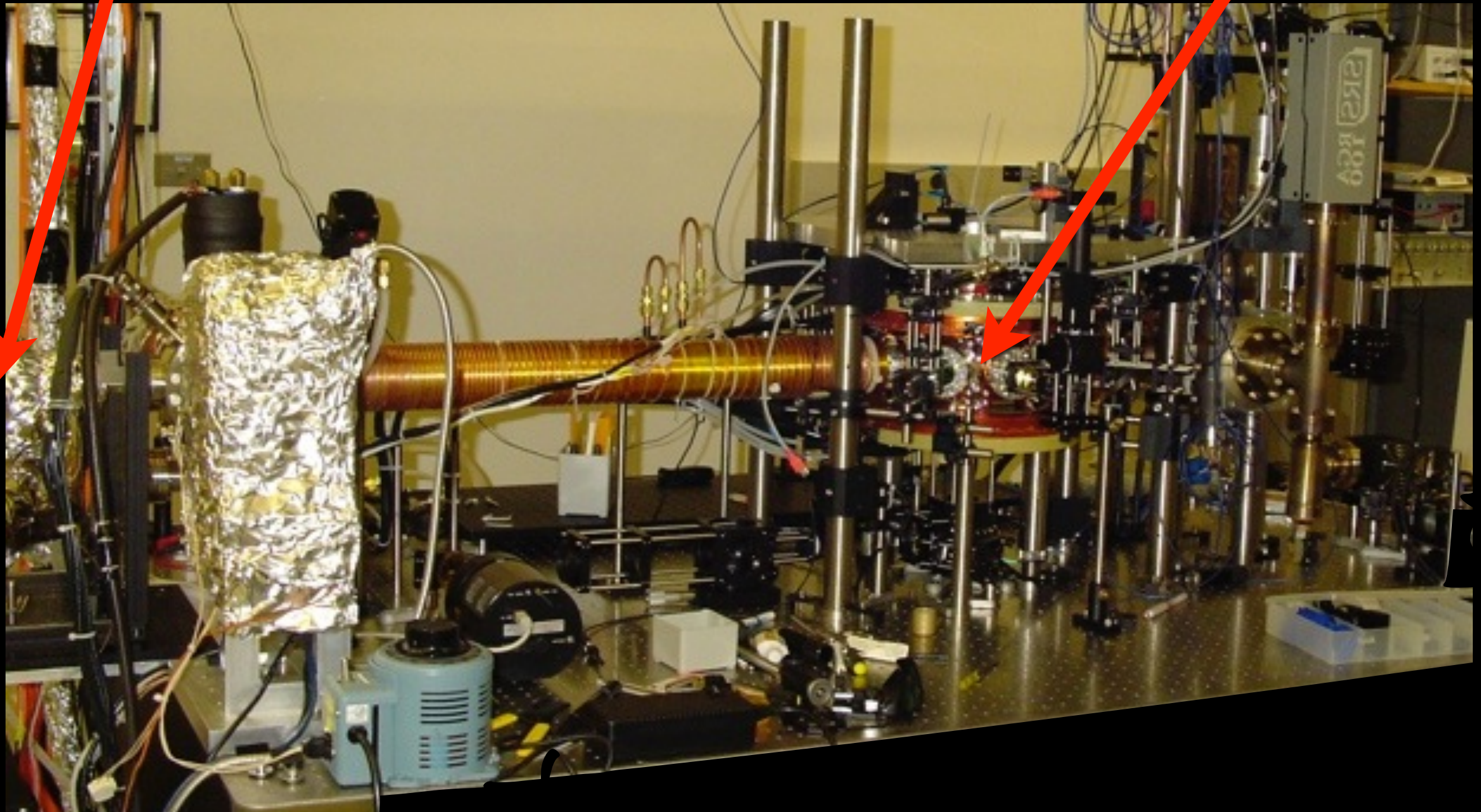
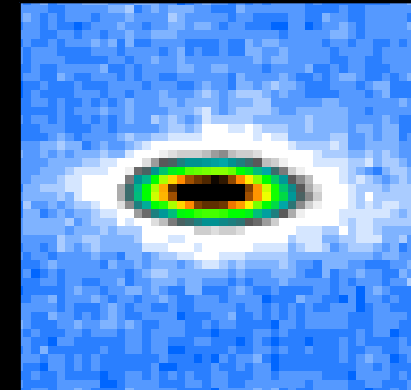
Starts like this

400 K



Ends here every 15 s

50 nK



# Anatomy of an experiment

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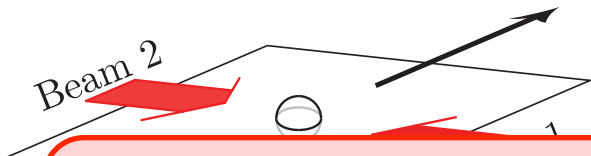
Laser cooling



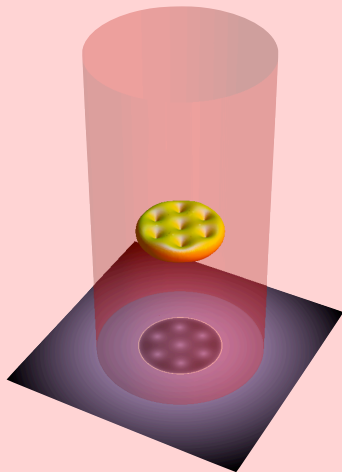
Evaporation



Experiment



Measurement



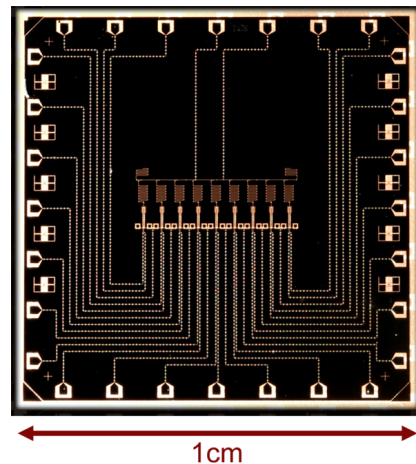
Total cycle time is about 15 seconds

We make a new BEC,  
measure it,  
destroy it,  
and repeat.

# How to engineer atomic quantum (and photonic) systems

## **Bottom-up engineering (Micromanaging quantum systems)**

Build the system up from well controlled quantum building blocks, e.g., qubits.



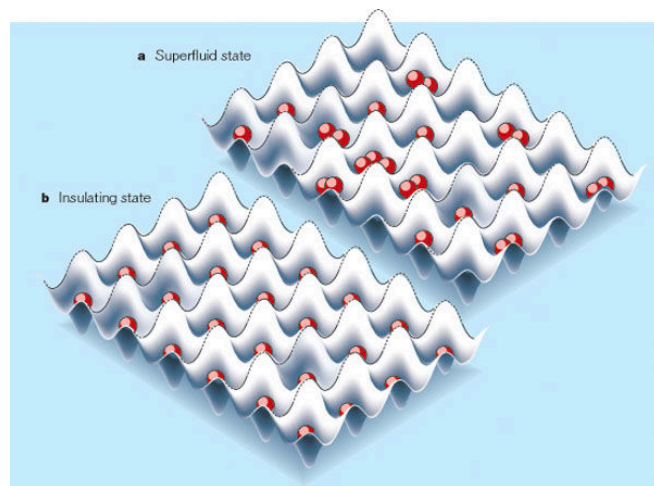
Martinis group / google; Science (2017)



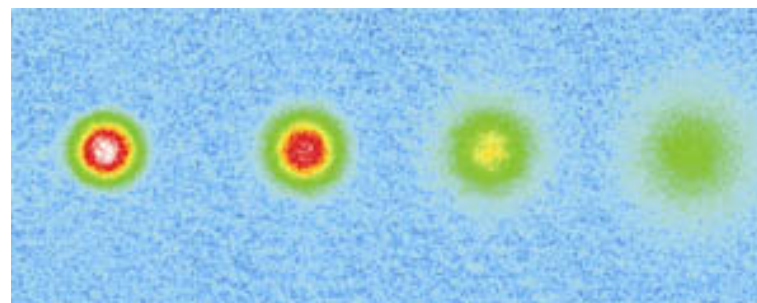
Monroe group; Nature (2017)

## **Hamiltonian engineering (Coaching quantum systems)**

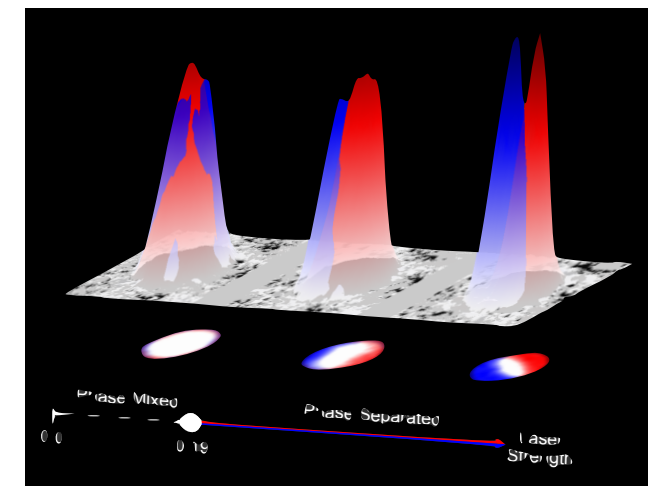
Build the Hamiltonian up with well calibrated control techniques



Bloch group; Nature (2002)



Jin group; Nature (2003)



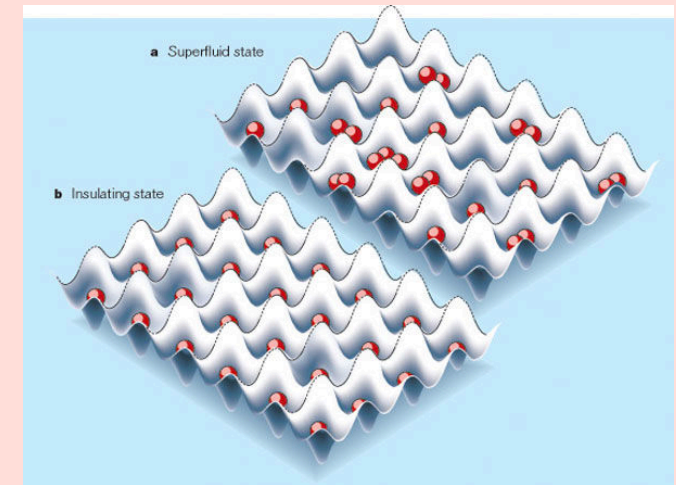
Lin et al; Nature (2011)

# Our tools

## Optical lattices

e.g., adding potentials

$$H = \frac{\hbar^2 \mathbf{k}^2}{2m} + \frac{V}{2} \cos(2k_r x) + \dots$$

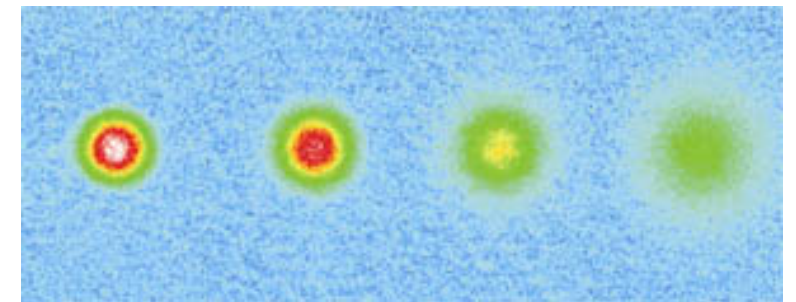


## Interaction tuning

e.g., Feshbach resonances

$$H = \dots + g_{3D} \delta(\mathbf{r}_i - \mathbf{r}_j) + \dots$$

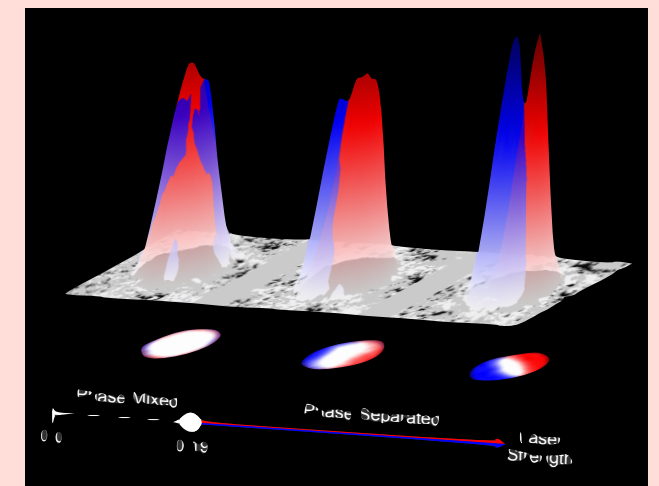
(really a regularized delta function...)



## Gauge fields / SOC

e.g., laser induced motion

$$H = \frac{[\mathbf{k} - \hat{A}(\mathbf{x})]^2}{2m} + \dots$$



# Lattice and gauge fields: why?

## Fundamental physics of novel matter

Quantum Hall (bosons or fermions, **magnetic field**),

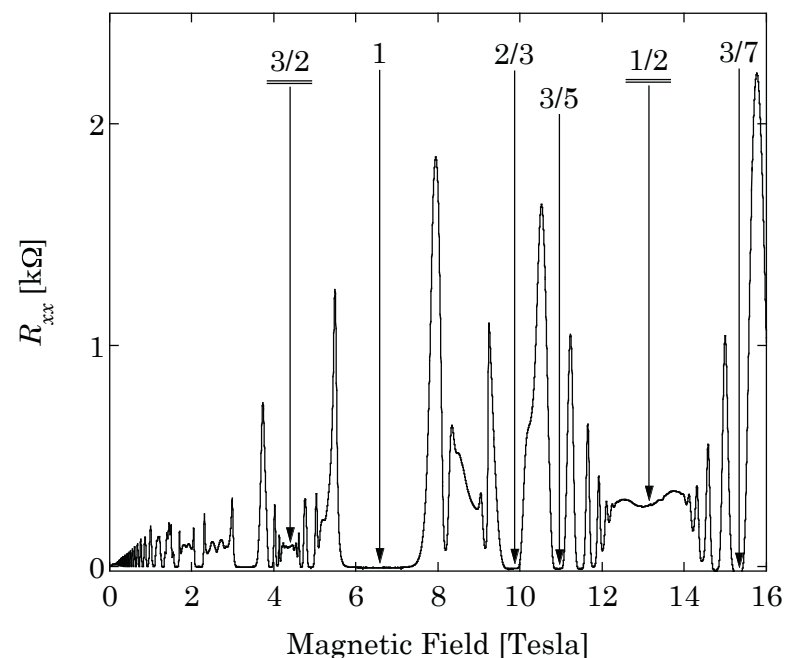
Quantum magnets (**spin-spin interactions, non-zero range**)

*p*-wave superconductors (fermions, spin polarized **p-wave interactions**)

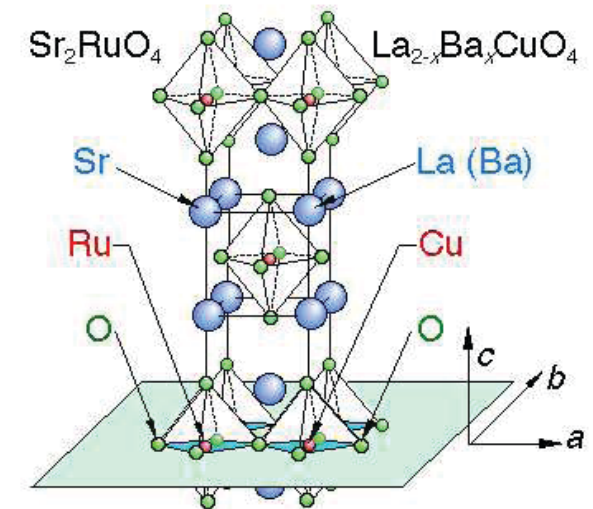
Topological insulators (generally with **spin-orbit coupling**)

(almost!) chaos

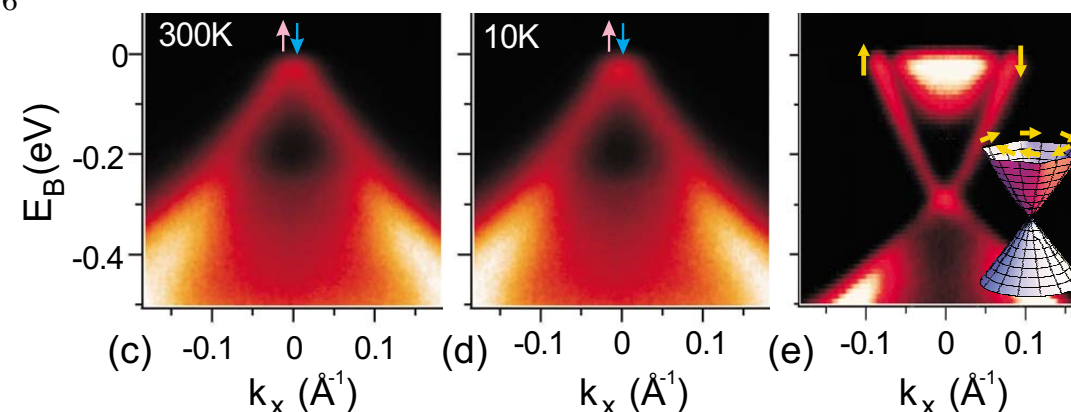
## FQHE Systems



## *p*-wave superconductivity

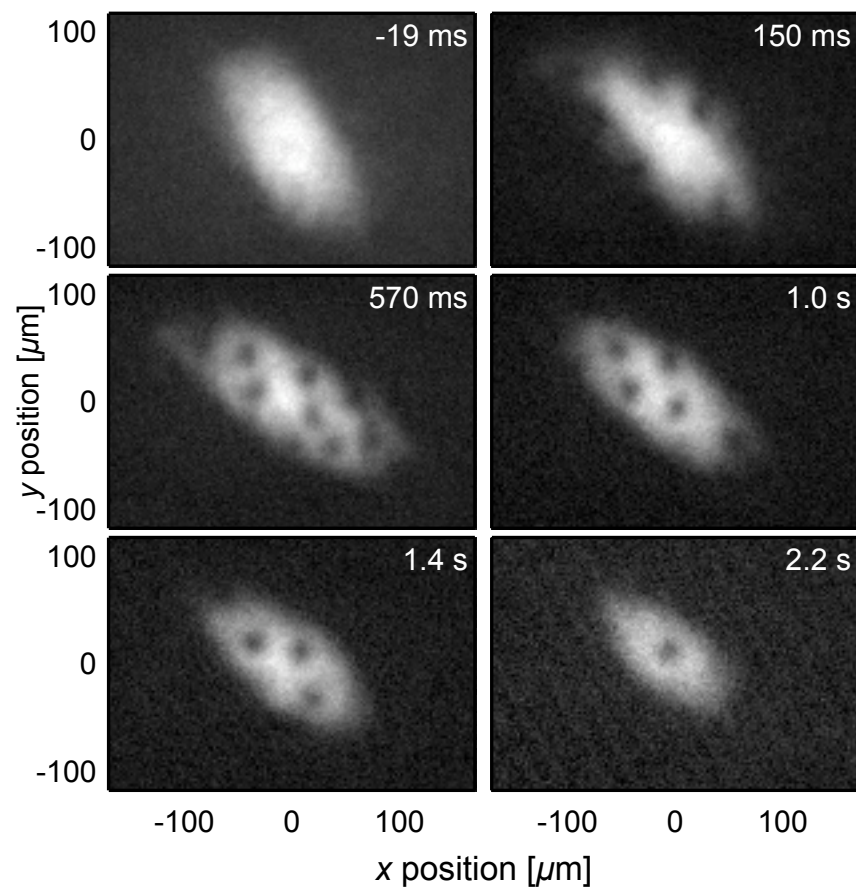
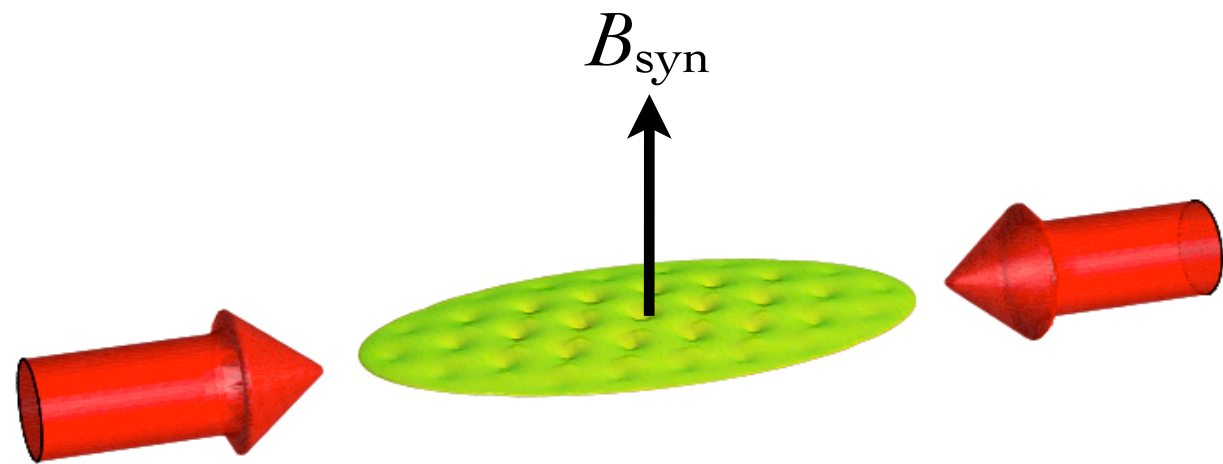


## Topological insulators

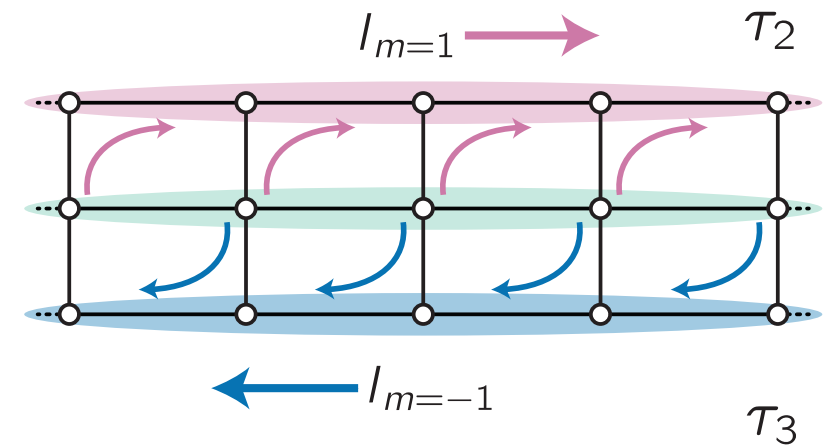


# Outline

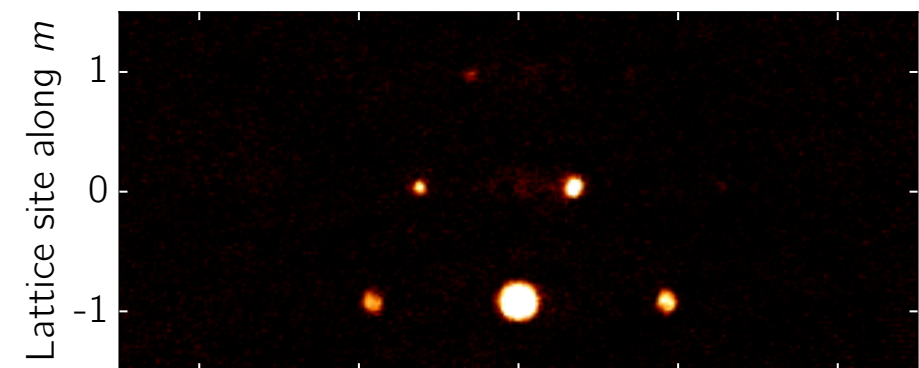
## Fields in free space



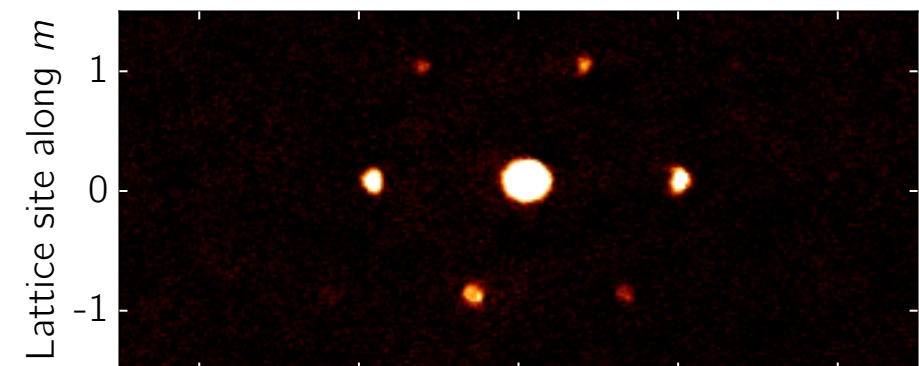
## Fields in synthetic dimensions

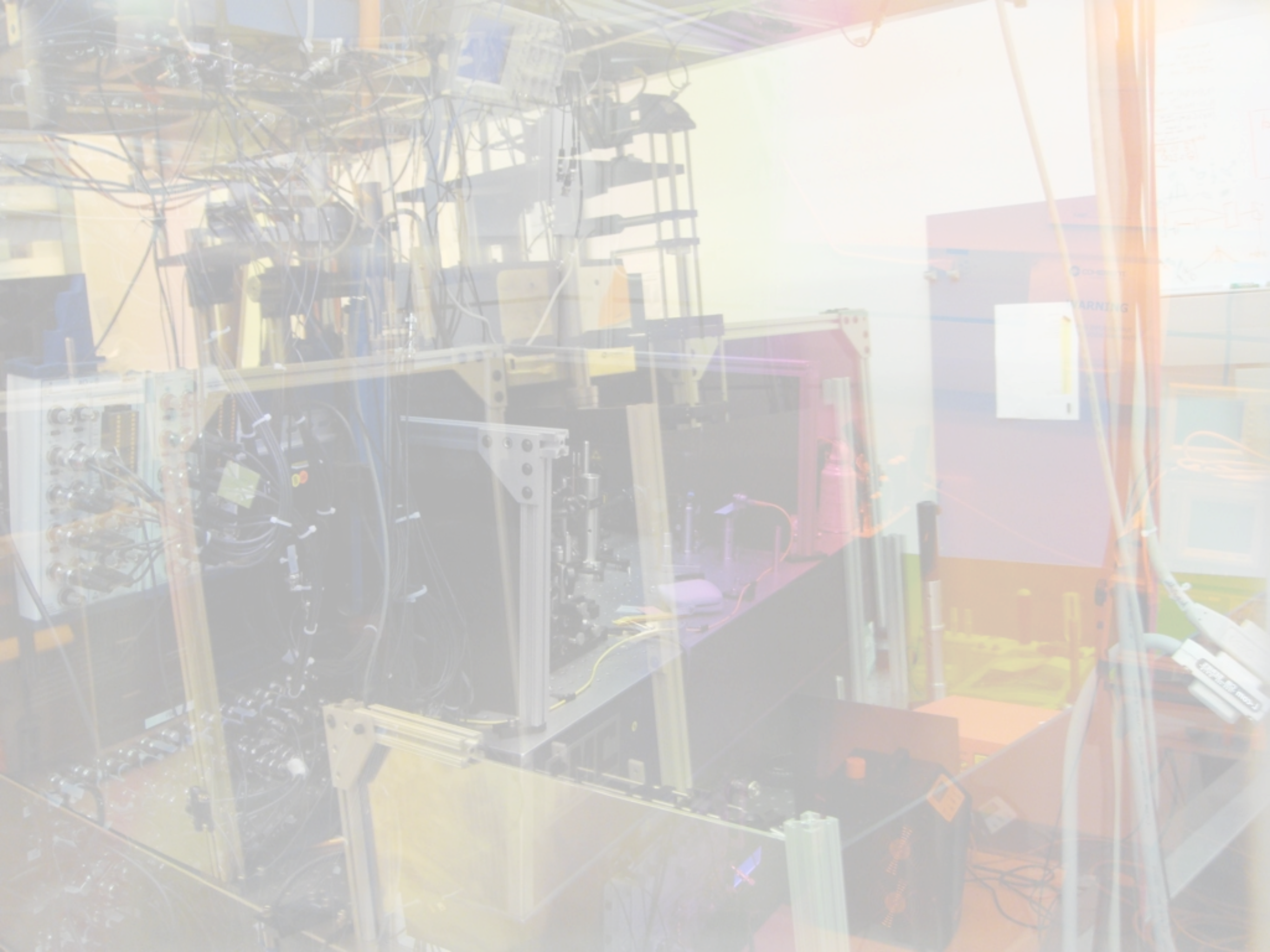


Edge



Bulk





# Synthetic **electromagnetism** with neutral atoms

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In this talk we will study the behavior of quantum matter in the presence of *static* magnetic fields



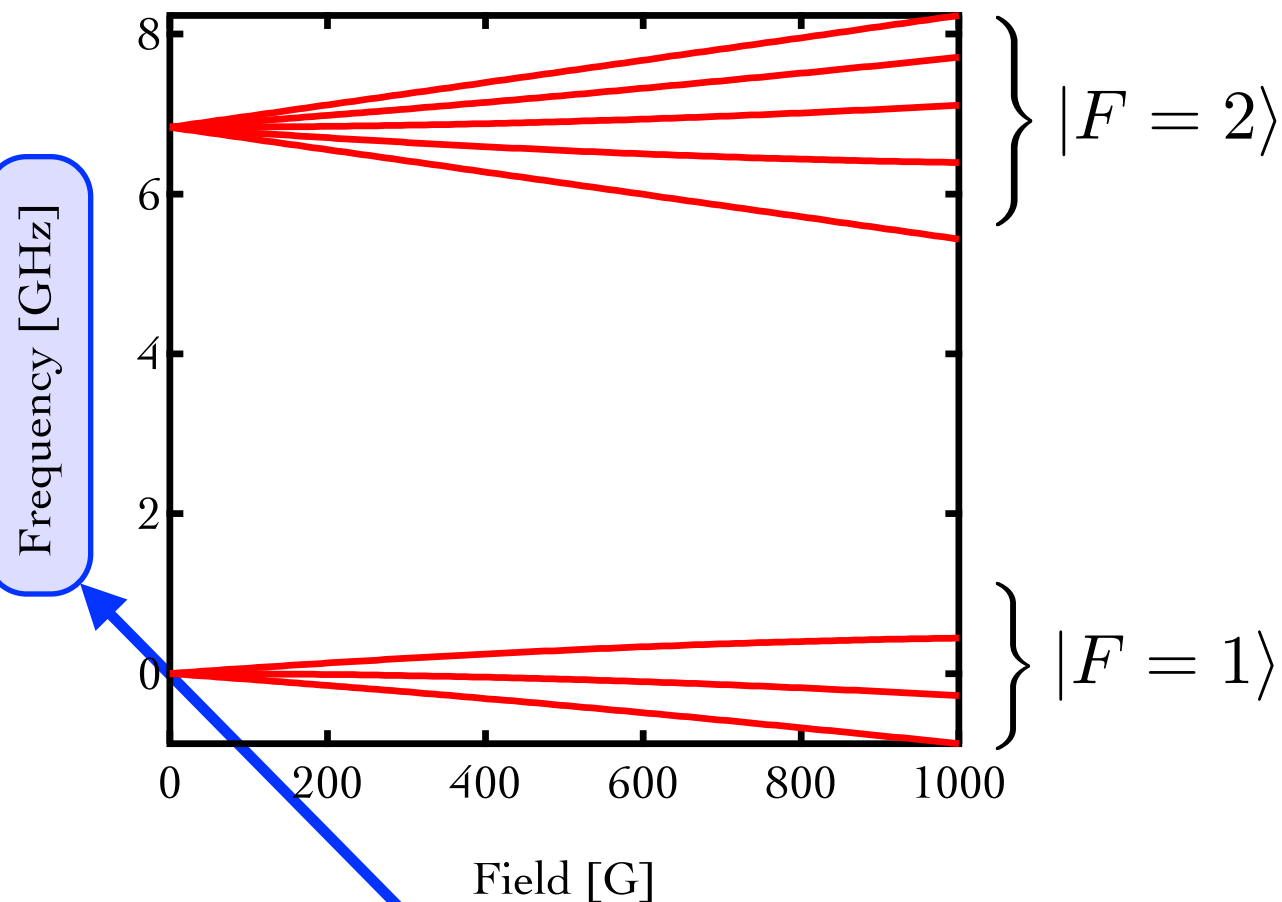
**NIST**

National Institute of Standards and Technology  
Technology Administration, U.S. Department of Commerce

# What do magnetic fields do?

## To spins

Zeeman effect, example of  $^{87}\text{Rb}$



Energy in dimensions of Hz

## To charges

### 1. Freshman mechanics

Mechanical variables and forces

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

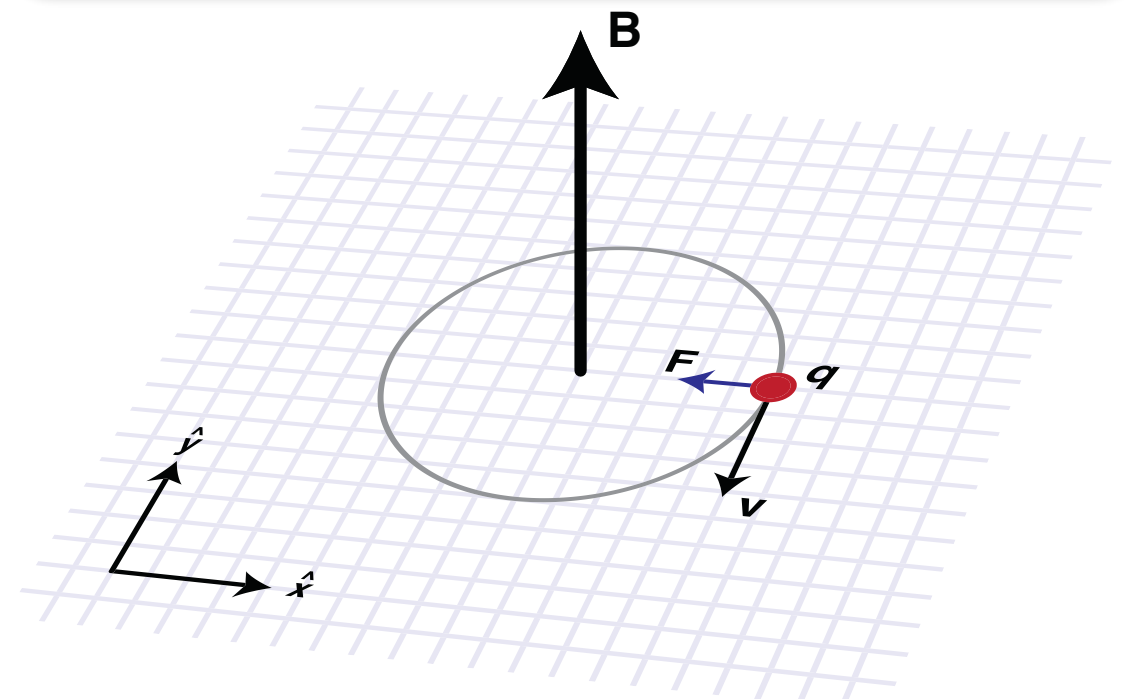
### 2. Junior mechanics

Canonical variables and vector potential

$$\mathbf{B} = \nabla \times \mathbf{A} \quad \text{e.g., } \mathbf{A} = \frac{B}{2}(x\hat{y} - y\hat{x})$$

$$H = \frac{(\mathbf{p} - q\mathbf{A})^2}{2m}$$

$$\dot{p}_j = -\frac{\partial}{\partial x_j} H, \quad \dot{x}_j = \frac{\partial}{\partial p_j} H$$



# What we want to create for neutral atoms

Single particle hamiltonian

$$\hat{H} = \frac{\hbar^2}{2m} \left[ \left( k_x - \frac{qA_x}{\hbar} \right)^2 + \left( k_y - \frac{qA_y}{\hbar} \right)^2 \right] + V(\mathbf{x})$$

How to control the *kinetic* energy term coupling between internal, spin, degrees of freedom.

Here I will be interested in a synthetic field normal to a 2D plane.

Some common gauge choices are:

$$A = \left\{ -\frac{By}{2}, \frac{Bx}{2}, 0 \right\}$$

Symmetric gauge: natural for rotating systems

$$A = \{0, Bx, 0\}$$

Landau gauge: relevant here

Expect the usual relations for fields

$$\mathbf{E} = -\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t} \quad B = \nabla \times A$$

# Synthetic electromagnetism with neutral atoms

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But wait our *neutral* atoms are  
*charge neutral!*



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# How to “charge” neutral particles

## Rotation

$$H_r = \frac{\hbar^2}{2m} \left[ \left( \hat{k}'_x - \frac{m\Omega}{\hbar} y \right)^2 + \left( \hat{k}'_y + \frac{m\Omega}{\hbar} x \right)^2 \right] + \frac{m(\omega^2 - \Omega^2)}{2} \mathbf{r}^2$$

JILA

MIT

## Raman Dressing

## How to simulate magnetic fields

(1) Rotation: the Hamiltonian in the rotating frame has an effective field. For high fields fine tuning is required.

**References:** V. Schweikhard et al PRL **92** 040404 (2004), J. R. Abo-Shaeer, C. Raman, and W. Ketterle PRL **88** 070409 (2002), K.W. Madison et al PRL **84** 806 (2000)

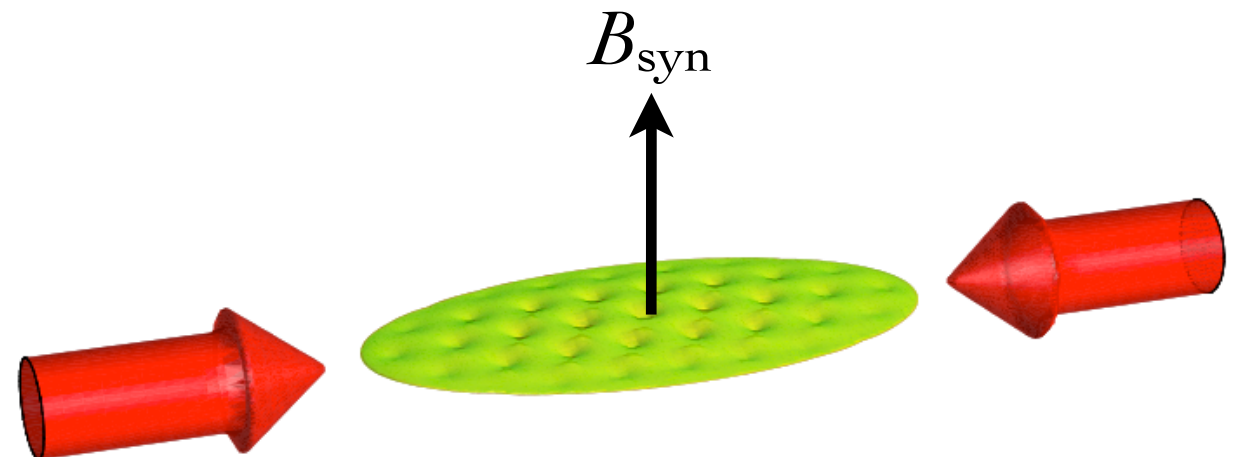
(2) Stroboscopic proposals.

(3) Immersions and others

**References:** A. Sørensen, et al PRL **94** p086803 (2005), A. Klein and D. Jaksch EPL, **85** 13001 (2009)

## Our approach

(4) Raman techniques.



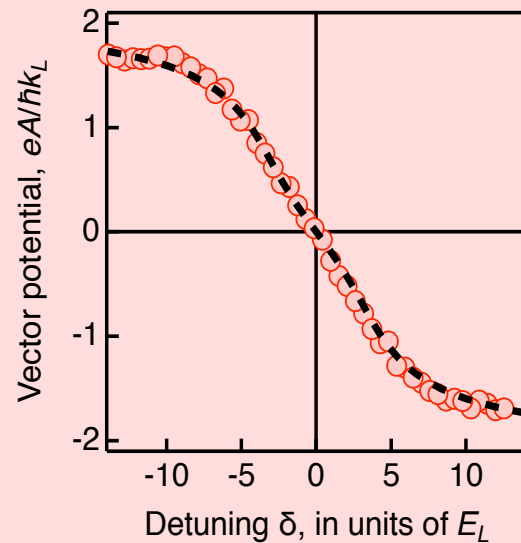
**Reference:** G. Juzeliūnas et al PRA **73** p025602 (2006)

# Today's outline

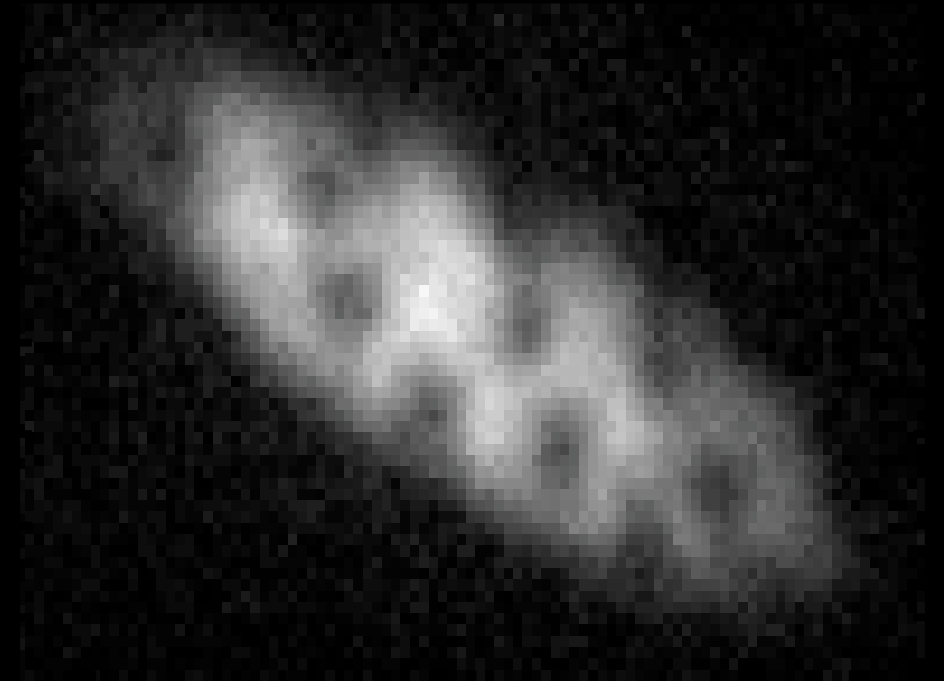
## A synthetic vector potential, created

Generate a synthetic vector potential

$$\hat{H} = \frac{\hbar^2}{2m} \left[ \left( k_x - \frac{qA_x}{\hbar} \right)^2 + \left( k_y - \frac{qA_y}{\hbar} \right)^2 \right] + V(\mathbf{x})$$



A electric and magnetic fields, revealed  
Spatial variation of  $A$  gives rise to a magnetic field



# Rubidium 87

| PERIODIC TABLE                    |                                                                                   |                |                                                                                              |                 |                                                                                                |                |                                                                                                               |               |                                                                                       |                |                                                                                                  |                 |                                                                                                        |                 |                                                                                                                 |                 |                               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| Atomic Properties of the Elements |                                                                                   |                |                                                                                              |                 |                                                                                                |                |                                                                                                               |               |                                                                                       |                |                                                                                                  |                 |                                                                                                        |                 |                                                                                                                 |                 |                                                                                                                   | National Institute of Standards and Technology<br>Technology Administration, U.S. Department of Commerce |                                                                                                     |                |                                                                                                                       |                 |                                                                                                             |                  |                                                                                                                    |                 |                                                                                                                |                |                                                                                                     |                 |                                      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| Group 1<br>IA                     |                                                                                   | Group 2<br>IIA |                                                                                              | Group 3<br>IIIB |                                                                                                | Group 4<br>IVB |                                                                                                               | Group 5<br>VB |                                                                                       | Group 6<br>VIB |                                                                                                  | Group 7<br>VIIB |                                                                                                        | Group 8<br>VIII |                                                                                                                 | Group 9<br>VIII |                                                                                                                   | Group 10<br>VIII                                                                                         |                                                                                                     | Group 11<br>IB |                                                                                                                       | Group 12<br>IIB |                                                                                                             | Group 13<br>IIIA |                                                                                                                    | Group 14<br>IVA |                                                                                                                | Group 15<br>VA |                                                                                                     | Group 16<br>VIA |                                                                                                              | Group 17<br>VIIA |                                                                                                                      | Group 18<br>VIIIA |                                                                                                                                  |    |                                                                                                                                     |    |                                                                                                                                 |    |                                                                                                                                    |    |                                                                                                                                  |    |                                                                                      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| 1                                 | <sup>2</sup> S <sub>1/2</sub><br><b>H</b><br>Hydrogen<br>1.00794<br>1s<br>13.5984 | 2              | <sup>1</sup> S <sub>0</sub><br><b>He</b><br>Helium<br>4.002602<br>1s <sup>2</sup><br>24.5874 | 3               | <sup>2</sup> S <sub>1/2</sub><br><b>Li</b><br>Lithium<br>6.941<br>1s <sup>2</sup> 2s<br>5.3917 | 4              | <sup>1</sup> S <sub>0</sub><br><b>Be</b><br>Beryllium<br>9.012182<br>1s <sup>2</sup> 2s <sup>2</sup><br>9.327 | 5             | <sup>2</sup> S <sub>1/2</sub><br><b>Na</b><br>Sodium<br>22.989770<br>[Ne]3s<br>5.1391 | 6              | <sup>1</sup> S <sub>0</sub><br><b>Mg</b><br>Magnesium<br>24.3040<br>[Ne]3s <sup>2</sup><br>7.642 | 7               | <sup>2</sup> D <sub>3/2</sub><br><b>Sc</b><br>Scandium<br>44.955910<br>[Ar]3d4s <sup>2</sup><br>6.5615 | 8               | <sup>3</sup> F <sub>2</sub><br><b>Ti</b><br>Titanium<br>47.867<br>[Ar]3d <sup>2</sup> 4s <sup>2</sup><br>6.8281 | 9               | <sup>4</sup> F <sub>3/2</sub><br><b>V</b><br>Vanadium<br>50.9415<br>[Ar]3d <sup>3</sup> 4s <sup>2</sup><br>6.7462 | 10                                                                                                       | <sup>5</sup> S <sub>2</sub><br><b>Cr</b><br>Chromium<br>51.9961<br>[Ar]3d <sup>5</sup> 4s<br>6.7665 | 11             | <sup>6</sup> S <sub>5/2</sub><br><b>Mn</b><br>Manganese<br>54.938049<br>[Ar]3d <sup>5</sup> 4s <sup>2</sup><br>7.4340 | 12              | <sup>5</sup> D <sub>4</sub><br><b>Fe</b><br>Iron<br>55.845<br>[Ar]3d <sup>6</sup> 4s <sup>2</sup><br>7.9024 | 13               | <sup>4</sup> F <sub>9/2</sub><br><b>Co</b><br>Cobalt<br>58.933200<br>[Ar]3d <sup>7</sup> 4s <sup>2</sup><br>7.8810 | 14              | <sup>3</sup> F <sub>4</sub><br><b>Ni</b><br>Nickel<br>58.6934<br>[Ar]3d <sup>8</sup> 4s <sup>2</sup><br>7.6398 | 15             | <sup>2</sup> S <sub>1/2</sub><br><b>Cu</b><br>Copper<br>63.546<br>[Ar]3d <sup>10</sup> 4s<br>7.7264 | 16              | <sup>1</sup> S <sub>0</sub><br><b>Zn</b><br>Zinc<br>65.409<br>[Ar]3d <sup>10</sup> 4s <sup>2</sup><br>9.3942 | 17               | <sup>2</sup> P <sub>1/2</sub><br><b>Ga</b><br>Gallium<br>69.723<br>[Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p<br>5.9993 | 18                | <sup>3</sup> P <sub>0</sub><br><b>Ge</b><br>Germanium<br>72.64<br>[Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>2</sup><br>7.8994 | 19 | <sup>4</sup> S <sub>3/2</sub><br><b>As</b><br>Arsenic<br>74.92160<br>[Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>3</sup><br>9.7886 | 20 | <sup>3</sup> P <sub>2</sub><br><b>Se</b><br>Selenium<br>78.96<br>[Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>4</sup><br>9.7524 | 21 | <sup>2</sup> P <sub>3/2</sub><br><b>Br</b><br>Bromine<br>79.904<br>[Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>5</sup><br>11.8138 | 22 | <sup>1</sup> S <sub>0</sub><br><b>Kr</b><br>Krypton<br>83.798<br>[Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>6</sup><br>13.9996 | 23 | <sup>2</sup> S <sub>1/2</sub><br><b>Rb</b><br>Rubidium<br>85.4678<br>[Kr]5s<br>4.1771 | 24 | <sup>1</sup> S <sub>0</sub><br><b>Sr</b><br>Strontium<br>87.62<br>[Kr]5s <sup>2</sup><br>5.699 | 25 | <sup>2</sup> D <sub>3/2</sub><br><b>Y</b><br>Yttrium<br>88.90585<br>[Kr]4d5s <sup>2</sup><br>6.2173 | 26 | <sup>3</sup> F <sub>2</sub><br><b>Zr</b><br>Zirconium<br>91.224<br>[Kr]4d <sup>2</sup> 5s <sup>2</sup><br>6.6339 | 27 | <sup>6</sup> D <sub>1/2</sub><br><b>Nb</b><br>Niobium<br>92.90638<br>[Kr]4d <sup>4</sup> 5s<br>6.7589 | 28 | <sup>7</sup> S <sub>3</sub><br><b>Mo</b><br>Molybdenum<br>95.94<br>[Kr]4d <sup>5</sup> 5s<br>7.0924 | 29 | <sup>6</sup> S <sub>5/2</sub><br><b>Tc</b><br>Technetium<br>(98)<br>[Kr]4d <sup>5</sup> 5s <sup>2</sup><br>7.28 | 30 | <sup>5</sup> F <sub>5</sub><br><b>Ru</b><br>Ruthenium<br>101.07<br>[Kr]4d <sup>7</sup> 5s<br>7.3605 | 31 | <sup>4</sup> F <sub>9/2</sub><br><b>Rh</b><br>Rhodium<br>102.90550<br>[Kr]4d <sup>8</sup> 5s<br>7.4589 | 32 | <sup>1</sup> S <sub>0</sub><br><b>Pd</b><br>Palladium<br>106.42<br>[Kr]4d <sup>10</sup><br>8.3369 | 33 | <sup>2</sup> S <sub>1/2</sub><br><b>Ag</b><br>Silver<br>107.8682<br>[Kr]4d <sup>10</sup> 5s<br>7.5762 | 34 | <sup>1</sup> S <sub>0</sub><br><b>Cd</b><br>Cadmium<br>112.411<br>[Kr]4d <sup>10</sup> 5s <sup>2</sup><br>8.9938 | 35 | <sup>2</sup> P <sub>1/2</sub><br><b>In</b><br>Indium<br>114.818<br>[Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p<br>5.7864 | 36 | <sup>3</sup> P <sub>0</sub><br><b>Sn</b><br>Tin<br>118.710<br>[Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>2</sup><br>7.3439 | 37 | <sup>4</sup> S <sub>3/2</sub><br><b>Sb</b><br>Antimony<br>121.760<br>[Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>3</sup><br>8.6084 | 38 | <sup>3</sup> P <sub>2</sub><br><b>Te</b><br>Tellurium<br>127.60<br>[Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>4</sup><br>9.0096 | 39 | <sup>2</sup> P <sub>3/2</sub><br><b>I</b><br>Iodine<br>126.90447<br>[Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>5</sup><br>10.4513 | 40 | <sup>1</sup> S <sub>0</sub><br><b>Xe</b><br>Xenon<br>131.293<br>[Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>6</sup><br>12.1298 | 41 | <sup>2</sup> S <sub>1/2</sub><br><b>Cs</b><br>Cesium<br>132.90545<br>[Xe]6s<br>3.8939 | 42 | <sup>1</sup> S <sub>0</sub><br><b>Ba</b><br>Barium<br>137.327<br>[Xe]6s <sup>2</sup><br>5.2117 | 43 | <sup>2</sup> D <sub>3/2</sub><br><b>La</b><br>Lanthanum<br>138.9055<br>[Xe]5d6s <sup>2</sup><br>5.5769 | 44 | <sup>1</sup> G <sub>4</sub><br><b>Ce</b><br>Cerium<br>140.116<br>[Xe]4f5d6s <sup>2</sup><br>5.5387 | 45 | <sup>4</sup> I <sub>9/2</sub><br><b>Pr</b><br>Praseodymium<br>140.90765<br>[Xe]4f36s <sup>2</sup><br>5.473 | 46 | <sup>5</sup> I <sub>4</sub><br><b>Nd</b><br>Neodymium<br>144.24<br>[Xe]4f36s <sup>2</sup><br>5.5250 | 47 | <sup>6</sup> H <sub>5/2</sub><br><b>Pm</b><br>Promethium<br>(145)<br>[Xe]4f36s <sup>2</sup><br>5.582 | 48 | <sup>7</sup> F <sub>0</sub><br><b>Sm</b><br>Samarium<br>150.36<br>[Xe]4f66s <sup>2</sup><br>5.6437 | 49 | <sup>8</sup> S <sub>7/2</sub><br><b>Eu</b><br>Europium<br>151.964<br>[Xe]4f76s <sup>2</sup><br>5.6704 | 50 | <sup>9</sup> D <sub>2</sub><br><b>Gd</b><br>Gadolinium<br>157.25<br>[Xe]4f75d6s <sup>2</sup><br>6.1498 | 51 | <sup>6</sup> H <sub>15/2</sub><br><b>Tb</b><br>Terbium<br>158.92534<br>[Xe]4f96s <sup>2</sup><br>5.8638 | 52 | <sup>5</sup> I <sub>8</sub><br><b>Dy</b><br>Dysprosium<br>162.500<br>[Xe]4f106s <sup>2</sup><br>5.9389 | 53 | <sup>3</sup> H <sub>6</sub><br><b>Ho</b><br>Holmium<br>164.93032<br>[Xe]4f116s <sup>2</sup><br>6.0215 | 54 | <sup>2</sup> F <sub>7/2</sub><br><b>Er</b><br>Erbium<br>167.259<br>[Xe]4f126s <sup>2</sup><br>6.1077 | 55 | <sup>1</sup> S <sub>0</sub><br><b>Tm</b><br>Thulium<br>168.93421<br>[Xe]4f136s <sup>2</sup><br>6.1843 | 56 | <sup>2</sup> D <sub>3/2</sub><br><b>Yb</b><br>Ytterbium<br>173.04<br>[Xe]4f146s <sup>2</sup><br>6.2542 | 57 | <sup>2</sup> D <sub>3/2</sub><br><b>Lu</b><br>Lutetium<br>174.967<br>[Xe]4f145d6s <sup>2</sup><br>5.4259 | 58 | <sup>2</sup> D <sub>3/2</sub><br><b>Ac</b><br>Actinium<br>227<br>[Rn]6d7s <sup>2</sup><br>5.17 | 59 | <sup>3</sup> F <sub>2</sub><br><b>Th</b><br>Thorium<br>232.0381<br>[Rn]6d27s <sup>2</sup><br>6.3067 | 60 | <sup>4</sup> K <sub>11/2</sub><br><b>Pa</b><br>Protactinium<br>231.03588<br>[Rn]5f26d7s <sup>2</sup><br>5.89 | 61 | <sup>5</sup> L <sub>6</sub><br><b>U</b><br>Uranium<br>238.02891<br>[Rn]5f36d7s <sup>2</sup><br>6.1941 | 62 | <sup>6</sup> L <sub>11/2</sub><br><b>Np</b><br>Neptunium<br>(237)<br>[Rn]5f46d7s <sup>2</sup><br>6.2657 | 63 | <sup>7</sup> F <sub>0</sub><br><b>Pu</b><br>Plutonium<br>(244)<br>[Rn]5f67s <sup>2</sup><br>6.0260 | 64 | <sup>8</sup> S <sub>7/2</sub><br><b>Am</b><br>Americium<br>(243)<br>[Rn]5f77s <sup>2</sup><br>5.9738 | 65 | <sup>9</sup> D <sub>2</sub><br><b>Cm</b><br>Curium<br>(247)<br>[Rn]5f76d7s <sup>2</sup><br>5.9914 | 66 | <sup>6</sup> H <sub>15/2</sub><br><b>Bk</b><br>Berkelium<br>(247)<br>[Rn]5f97s <sup>2</sup><br>6.1979 | 67 | <sup>5</sup> I <sub>8</sub><br><b>Cf</b><br>Californium<br>(251)<br>[Rn]5f107s <sup>2</sup><br>6.2817 | 68 | <sup>4</sup> I <sub>15/2</sub><br><b>Es</b><br>Einsteinium<br>(252)<br>[Rn]5f117s <sup>2</sup><br>6.42 | 69 | <sup>3</sup> H <sub>6</sub><br><b>Fm</b><br>Fermium<br>(257)<br>[Rn]5f127s <sup>2</sup><br>6.50 | 70 | <sup>2</sup> F <sub>7/2</sub><br><b>Md</b><br>Mendelevium<br>(258)<br>[Rn]5f137s <sup>2</sup><br>6.58 | 71 | <sup>1</sup> S <sub>0</sub><br><b>No</b><br>Nobelium<br>(259)<br>[Rn]5f147s <sup>2</sup><br>6.65 | 72 | <sup>2</sup> P <sub>1/2</sub><br><b>Lr</b><br>Lawrencium<br>(262)<br>[Rn]5f147s27p?<br>4.9 ? |

**Frequently used fundamental physical constants**

For the most accurate values of these and other constants, visit [physics.nist.gov/constants](https://physics.nist.gov/constants)  
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of <sup>133</sup>Cs

|                          |                                   |                                              |                                     |
|--------------------------|-----------------------------------|----------------------------------------------|-------------------------------------|
| speed of light in vacuum | <i>c</i>                          | 299 792 458 m s <sup>-1</sup>                | (exact)                             |
| Planck constant          | <i>h</i>                          | 6.6261 × 10 <sup>-34</sup> J s               | ( <i>h</i> = <i>h</i> /2 <i>π</i> ) |
| elementary charge        | <i>e</i>                          | 1.6022 × 10 <sup>-19</sup> C                 |                                     |
| electron mass            | <i>m<sub>e</sub></i>              | 9.1094 × 10 <sup>-31</sup> kg                |                                     |
|                          | <i>m<sub>e</sub>c<sup>2</sup></i> | 0.5110 MeV                                   |                                     |
| proton mass              | <i>m<sub>p</sub></i>              | 1.6726 × 10 <sup>-27</sup> kg                |                                     |
| fine-structure constant  | <i>α</i>                          | 1/137.036                                    |                                     |
| Rydberg constant         | <i>R<sub>∞</sub></i>              | 10 973 732 m <sup>-1</sup>                   |                                     |
|                          | <i>R<sub>∞</sub>c</i>             | 3.289 842 × 10 <sup>15</sup> Hz              |                                     |
|                          | <i>R<sub>∞</sub>hc</i>            | 13.6057 eV                                   |                                     |
| Boltzmann constant       | <i>k</i>                          | 1.3807 × 10 <sup>-23</sup> J K <sup>-1</sup> |                                     |

**Physics Laboratory**  
[physics.nist.gov](https://physics.nist.gov)

**Standard Reference Data Group**  
[www.nist.gov/srd](https://www.nist.gov/srd)

**Legend:**

- Solids
- Liquids
- Gases
- Artificially Prepared

**Atomic Properties of the Elements**

Atomic Number, Symbol, Name, Atomic Weight, Ground-state Configuration, Ionization Energy (eV)

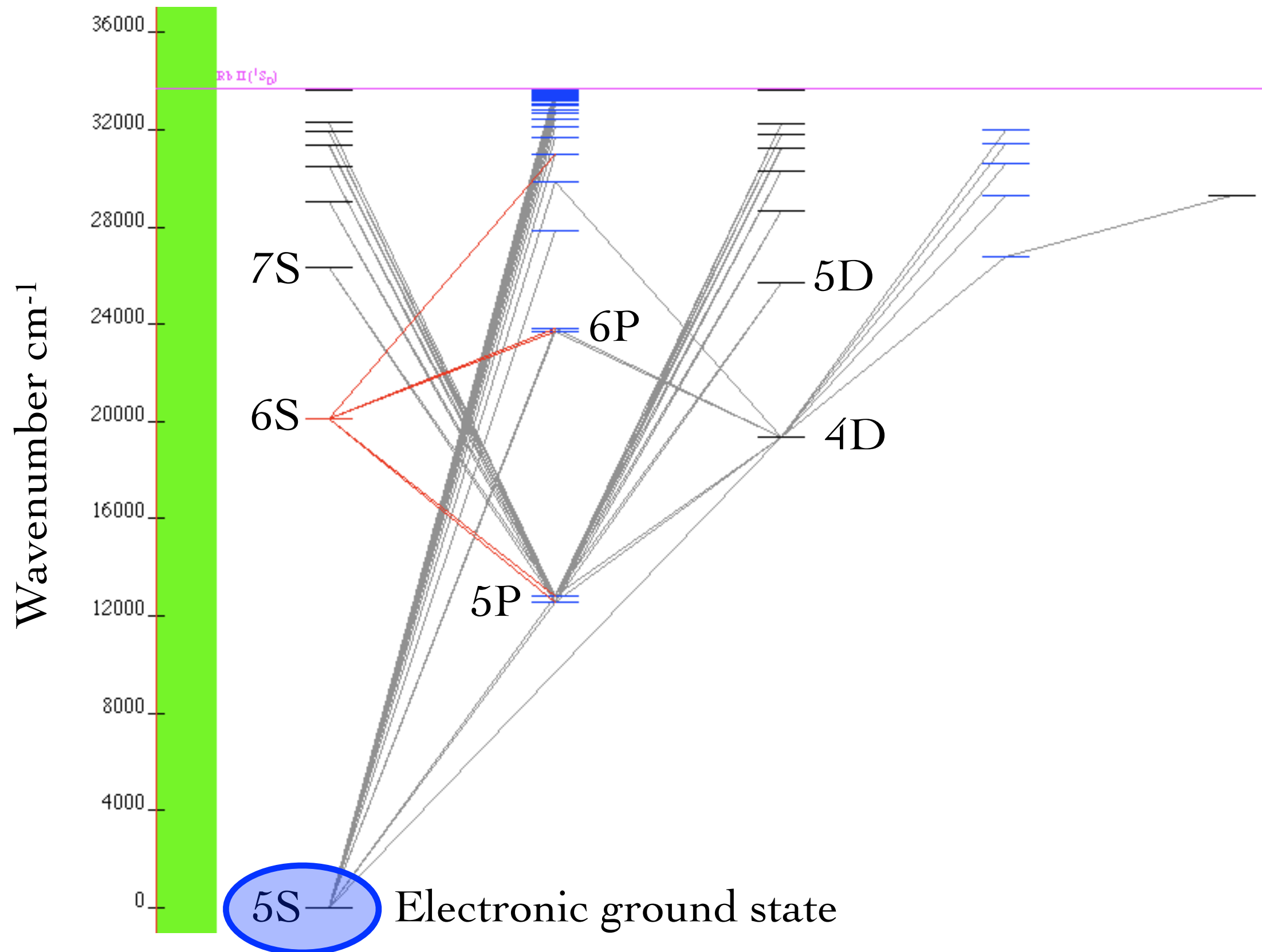
Example: **58 Ce** Cerium, 140.116, [Xe]4f5d6s<sup>2</sup>, 5.5387

<sup>†</sup>Based upon <sup>12</sup>C. () indicates the mass number of the most stable isotope.

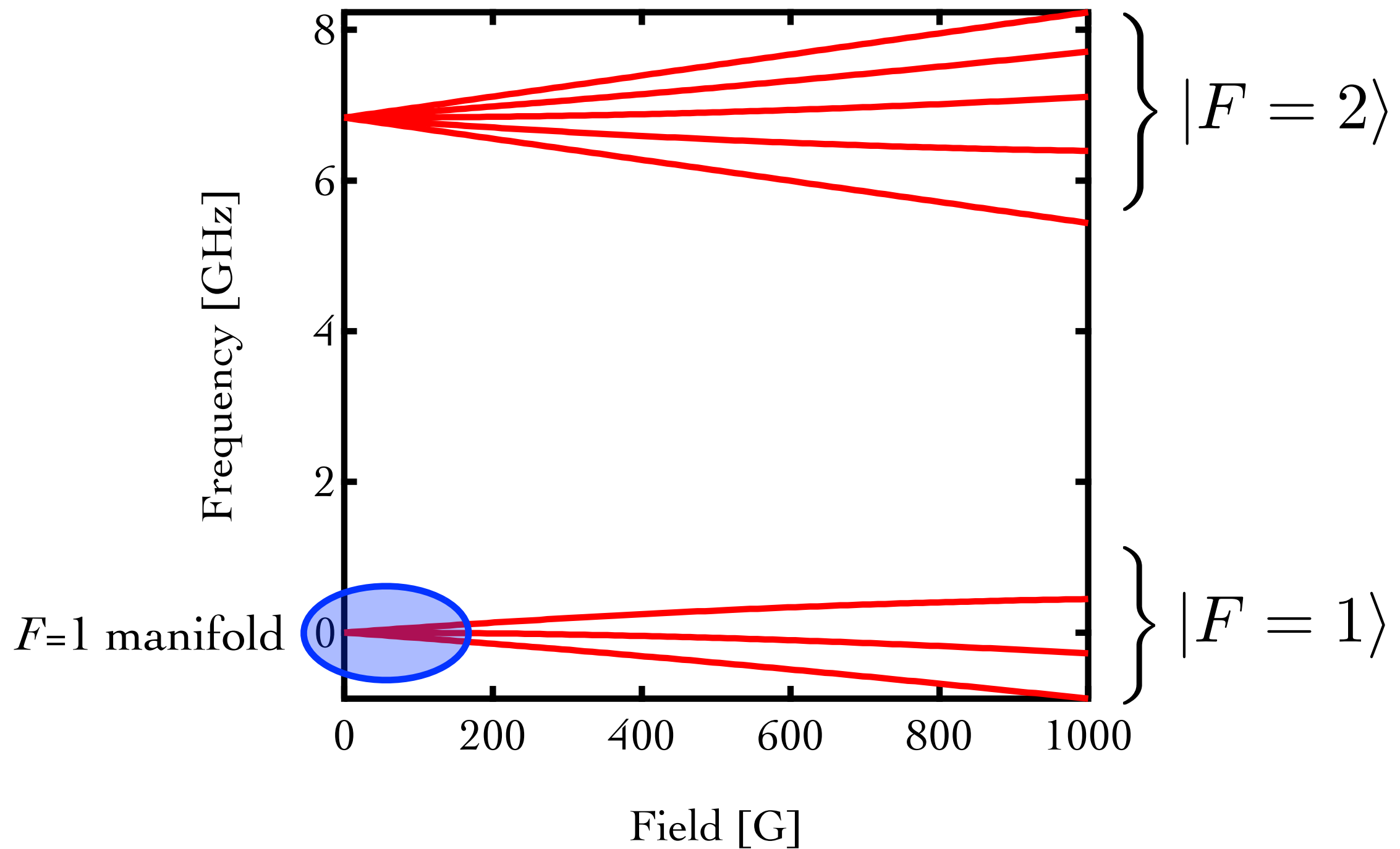
For a description of the data, visit [physics.nist.gov/data](https://physics.nist.gov/data)

NIST SP 966 (September 2003)

# Rubidium 87: Level structure



# Rubidium 87: $5S_{1/2}$ ground state

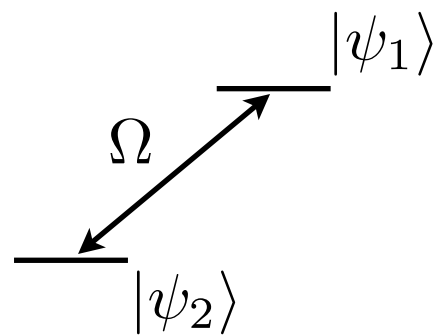


# All the atomic physics you need to know

## Schematic

Two levels coupled together

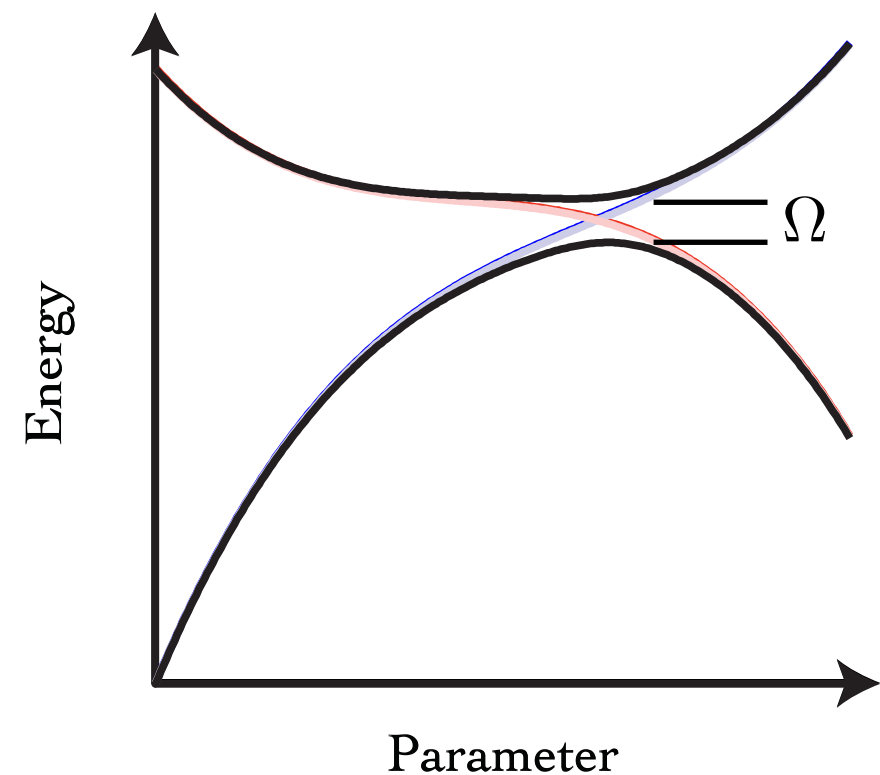
Energy



$$H = \begin{pmatrix} E_1 & \Omega/2 \\ \Omega/2 & E_2 \end{pmatrix}$$

## Graphic result

Avoided crossings

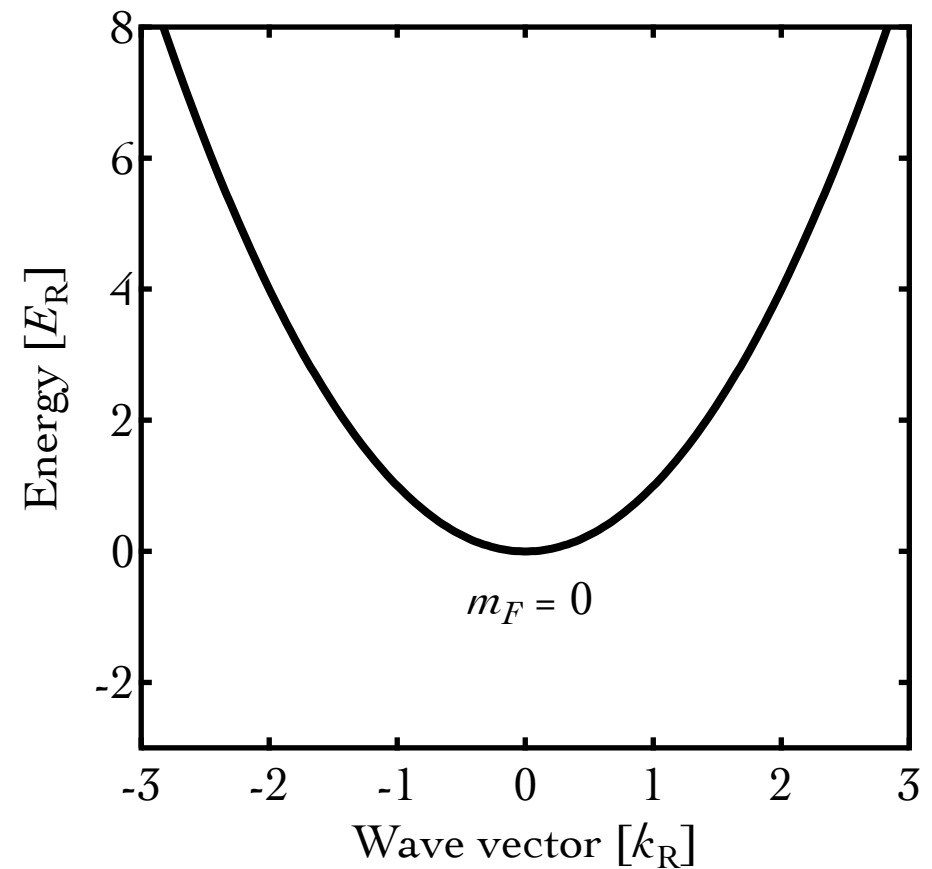
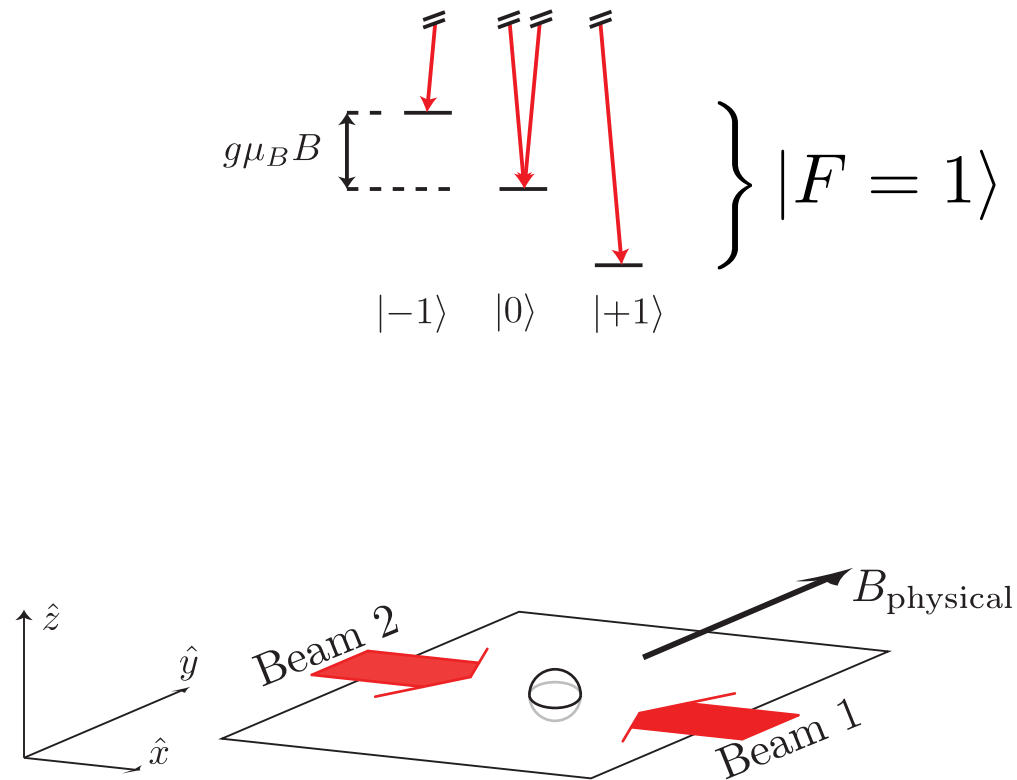


# Atom light interaction: pictures

## Atom light interaction

Given the following geometry and levels

## Coupled States



## Dimensions

$$k_R = \frac{2\pi}{\lambda}, \quad E_R = \frac{\hbar^2 k_R^2}{2m}$$

$$E_R \approx h \times 3 \text{ kHz} = k_B \times 140 \text{ nK}$$

## References

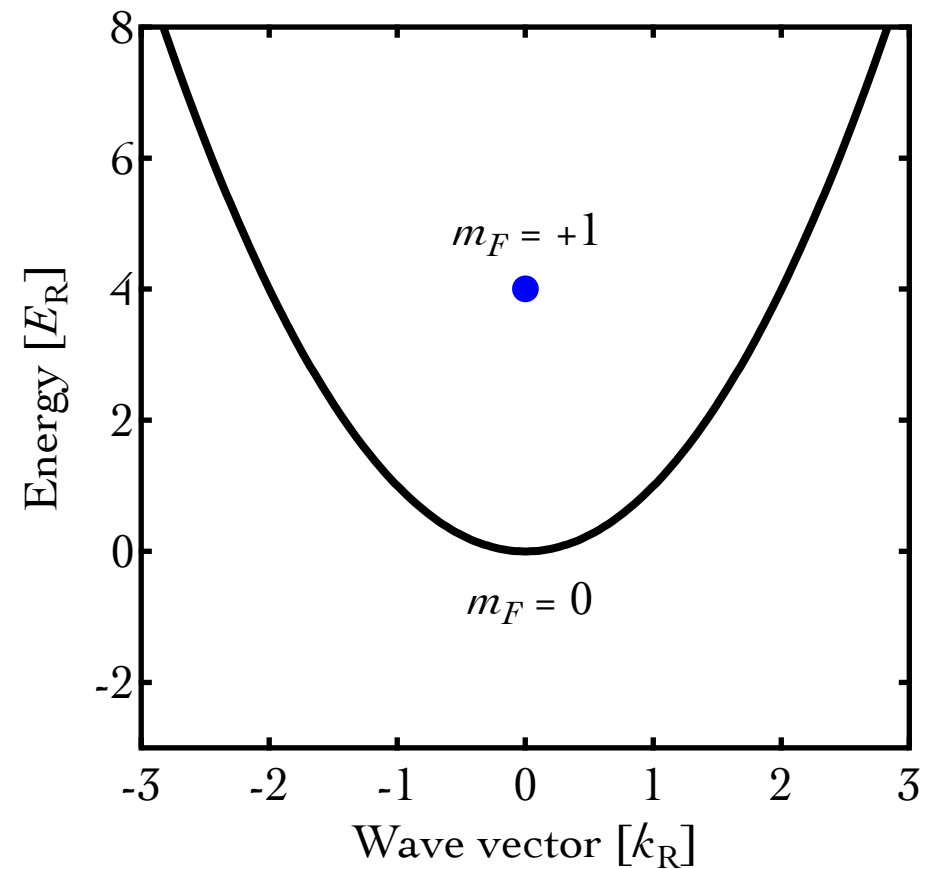
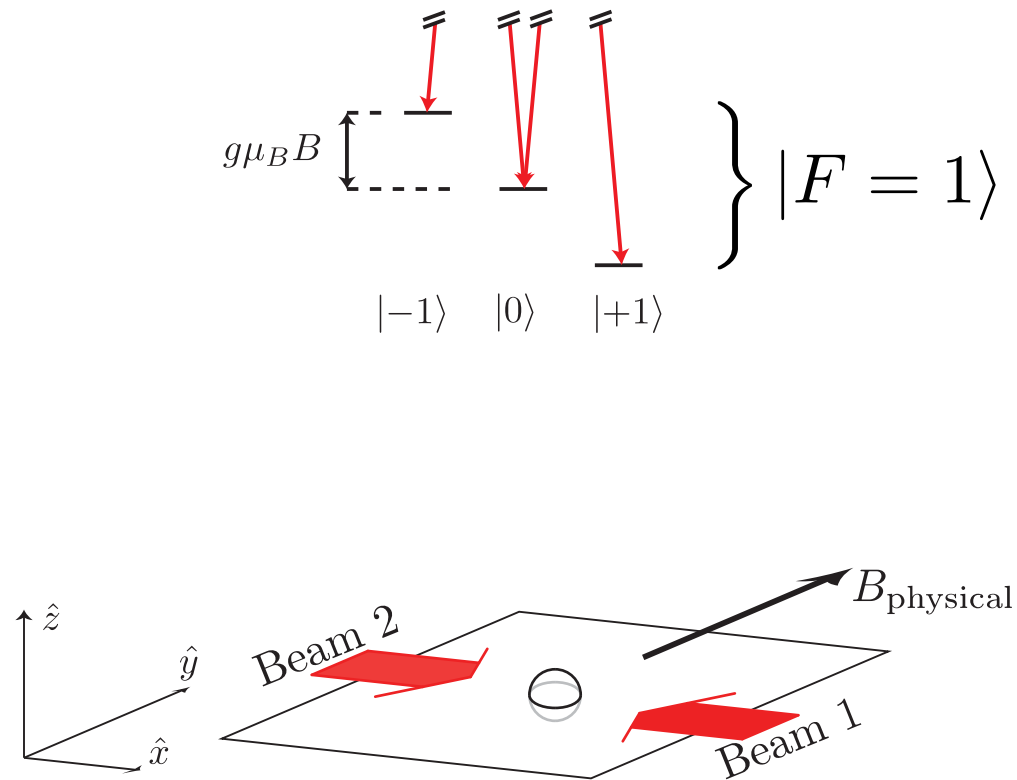
- [1] Juzeliūnas, et al., PRA 025602 **73** (2006), + earlier pubs
- [2] S.-L. Zhu, et al., PRL 240401 **97** (2006)
- [3] Günter et al, PRA **79** 011604 (2009)
- [4] IBS, PRA 063613 **79** (2009)

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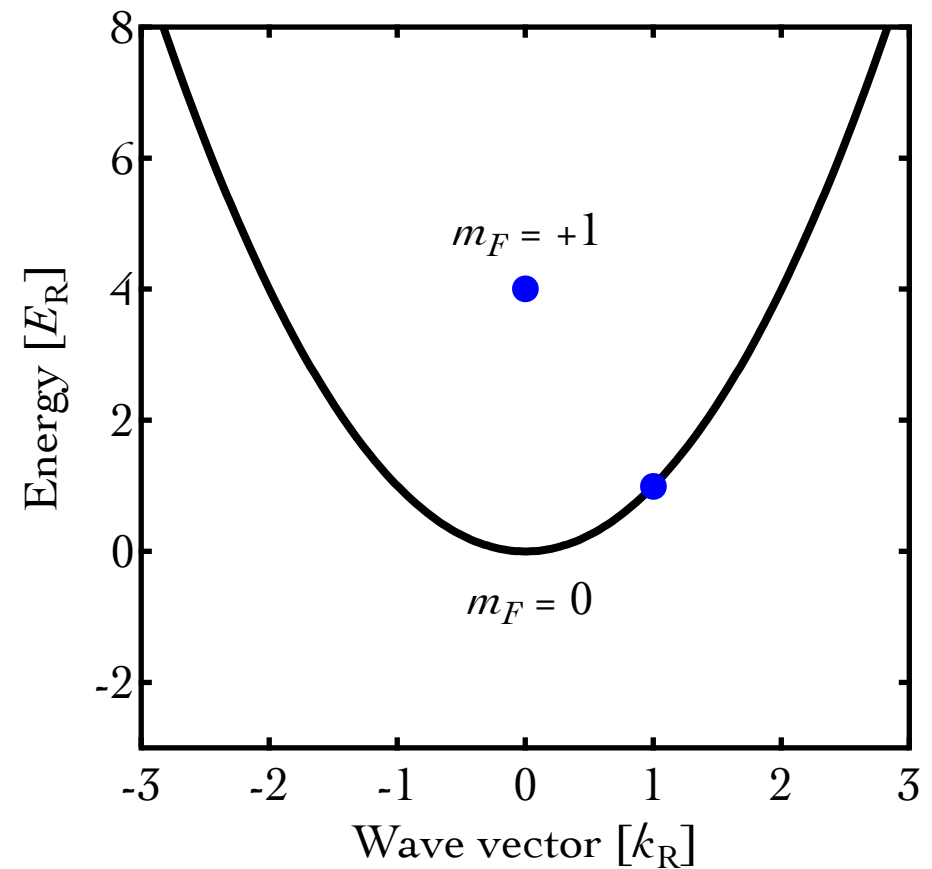
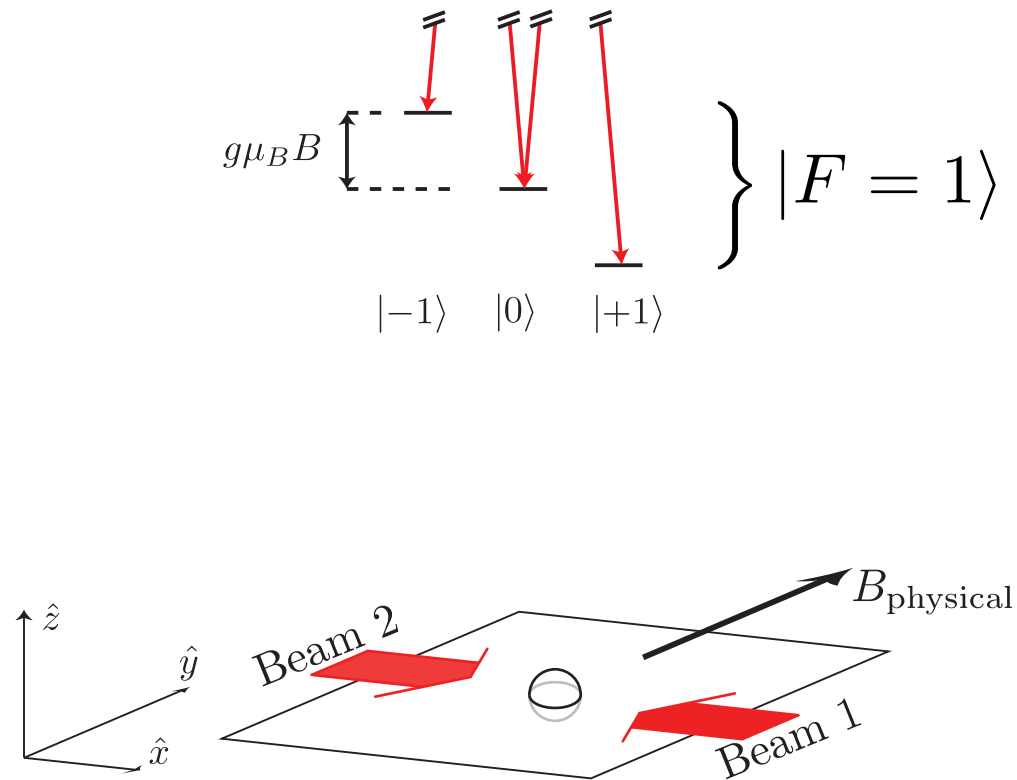
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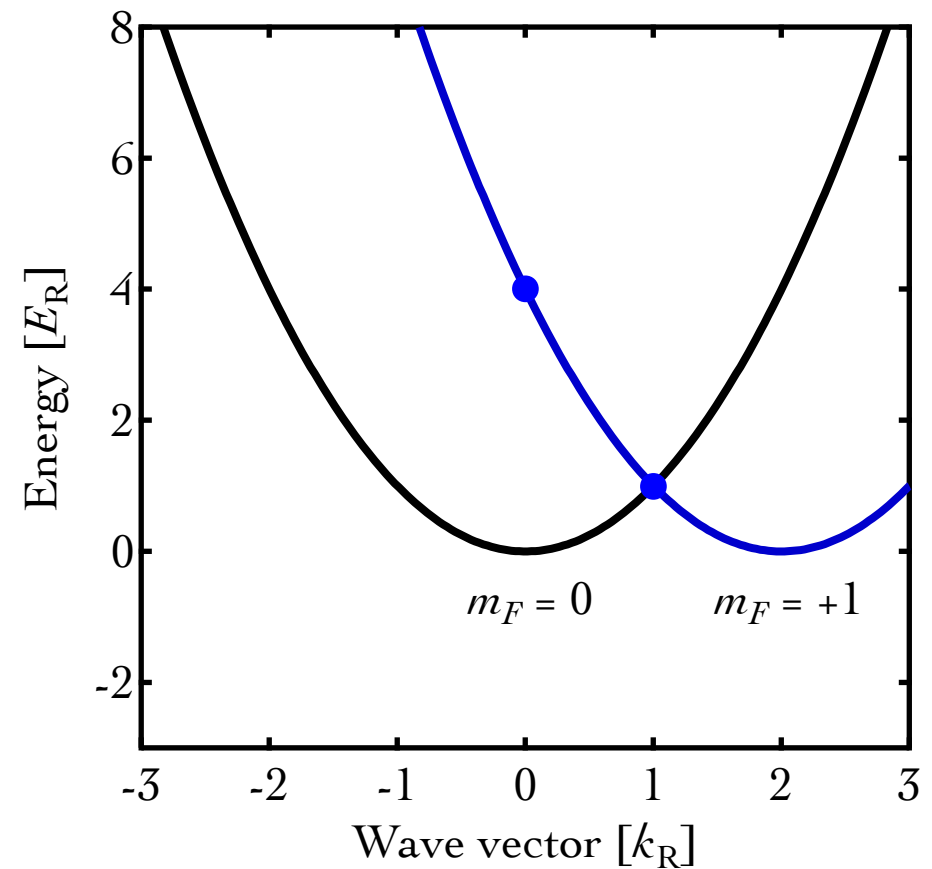
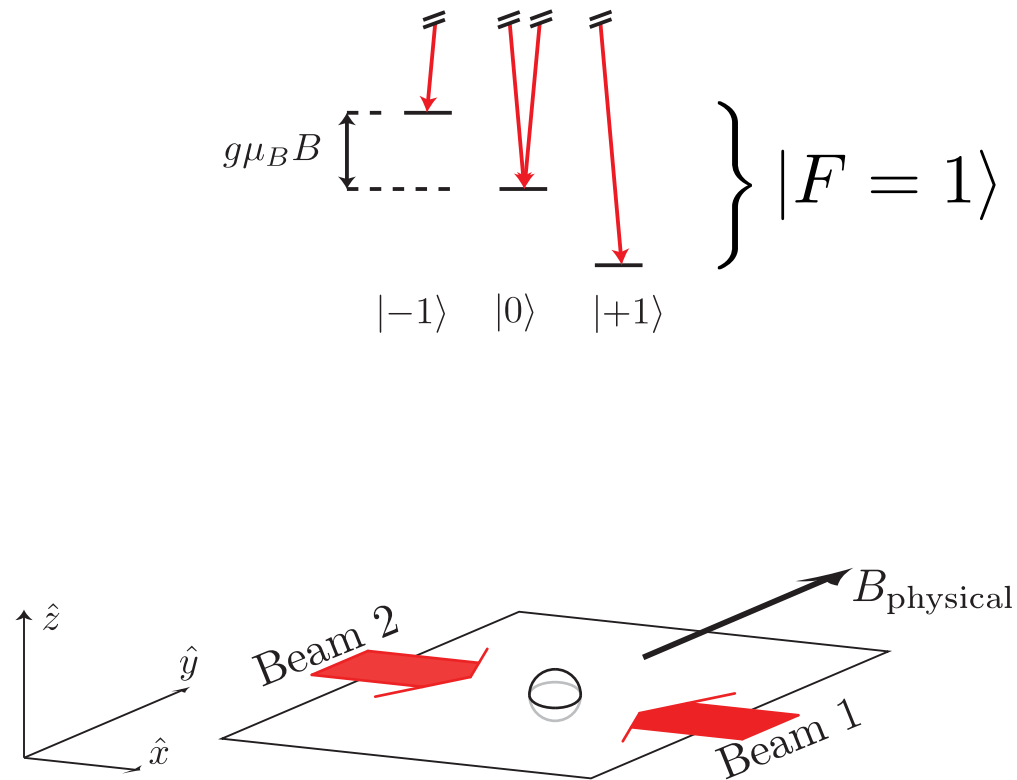
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- [2] S.-L. Zhu, et al., PRL 240401 **97** (2006)
- [3] Günter et al, PRA **79** 011604 (2009)
- [4] IBS, PRA 063613 **79** (2009)

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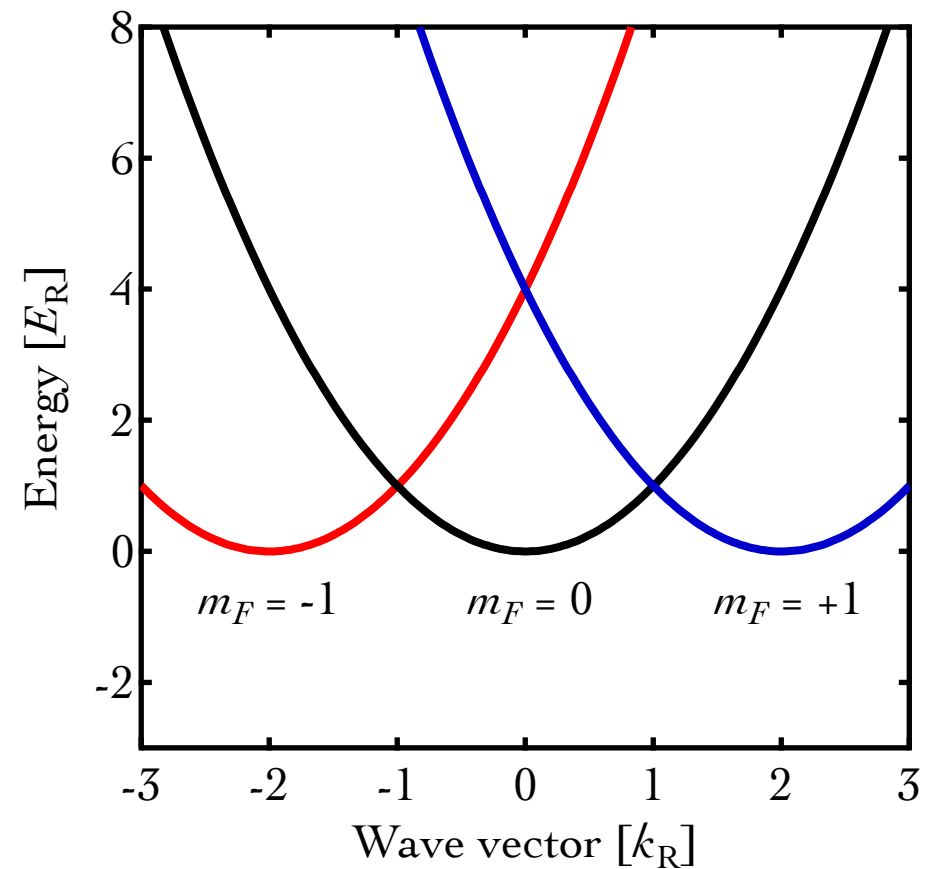
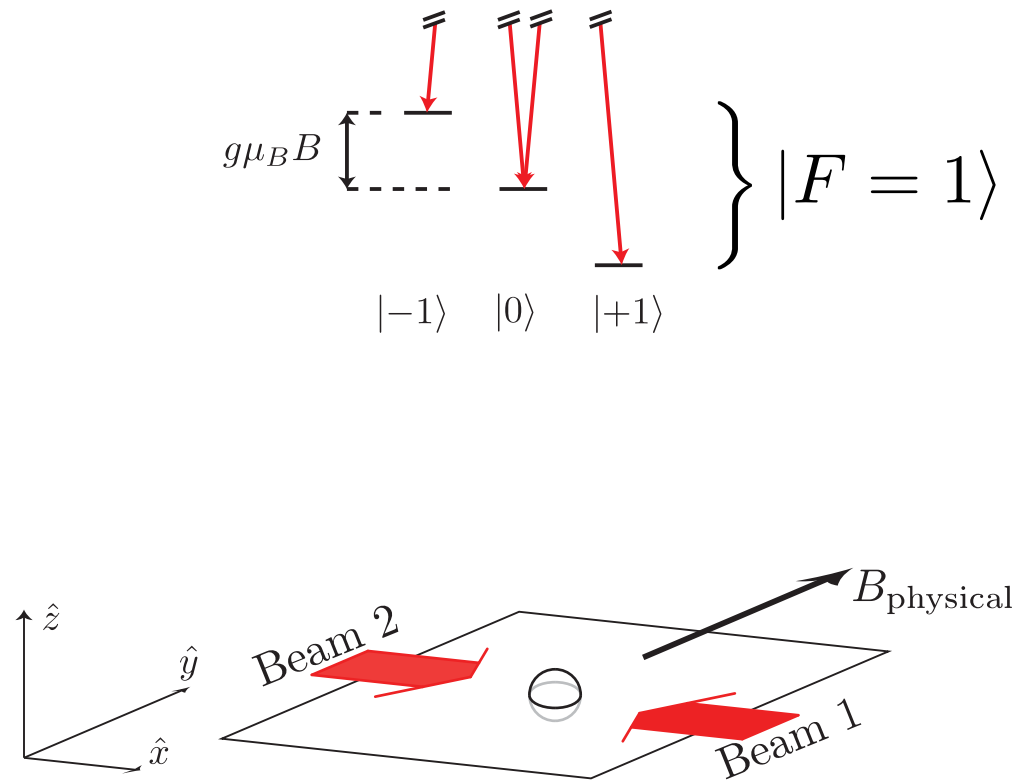
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- [3] Günter et al, PRA **79** 011604 (2009)
- [4] IBS, PRA 063613 **79** (2009)

# Atom light interaction: pictures

## Atom light interaction

Given the following geometry and levels

## Coupled States



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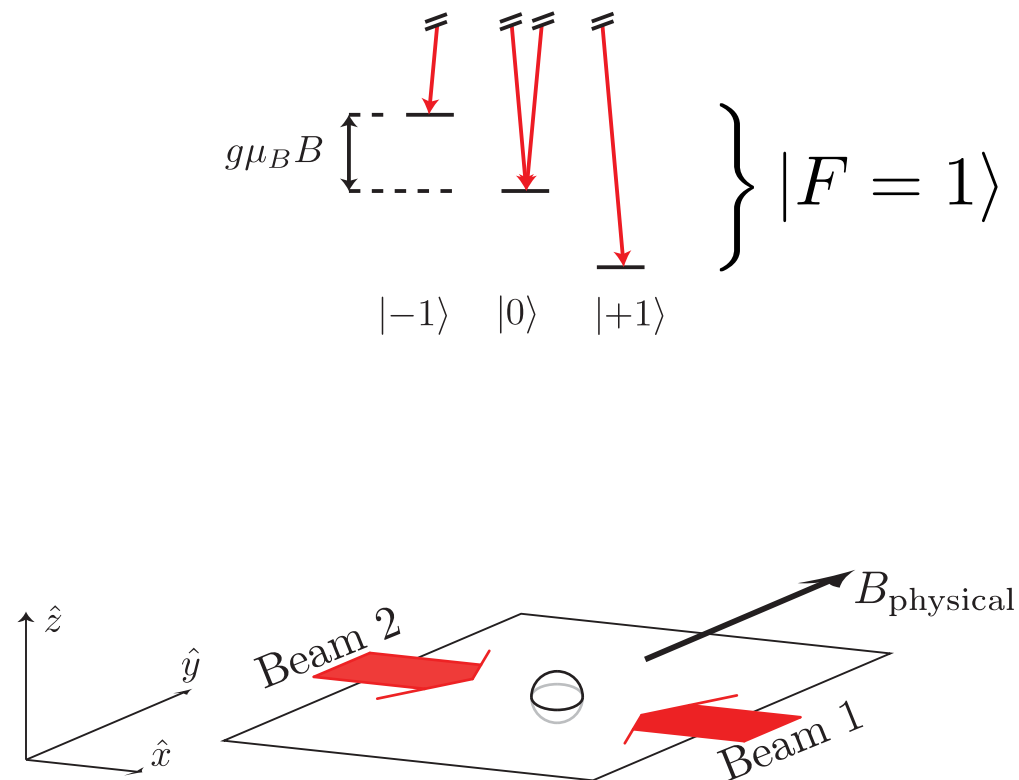
## References

- [1] Juzeliūnas, et al., PRA 025602 **73** (2006), + earlier pubs
- [2] S.-L. Zhu, et al., PRL 240401 **97** (2006)
- [3] Günter et al, PRA **79** 011604 (2009)
- [4] IBS, PRA 063613 **79** (2009)

# Atom light interaction: pictures

## Atom light interaction

Given the following geometry and levels



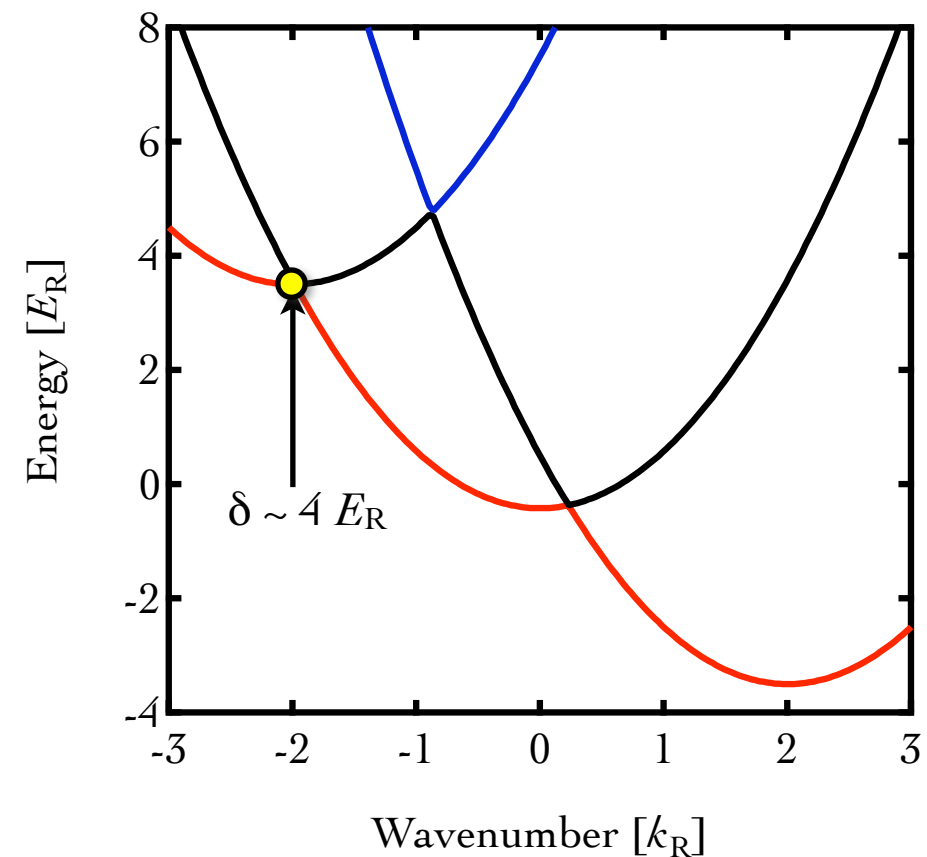
## Dimensions

$$k_R = \frac{2\pi}{\lambda}, \quad E_R = \frac{\hbar^2 k_R^2}{2m}$$

$$E_R \approx h \times 3 \text{ kHz} = k_B \times 140 \text{ nK}$$

## Coupled States

States will be labeled by:  
(1) the “band index” and by  
(2) a quasi-momentum  $k$



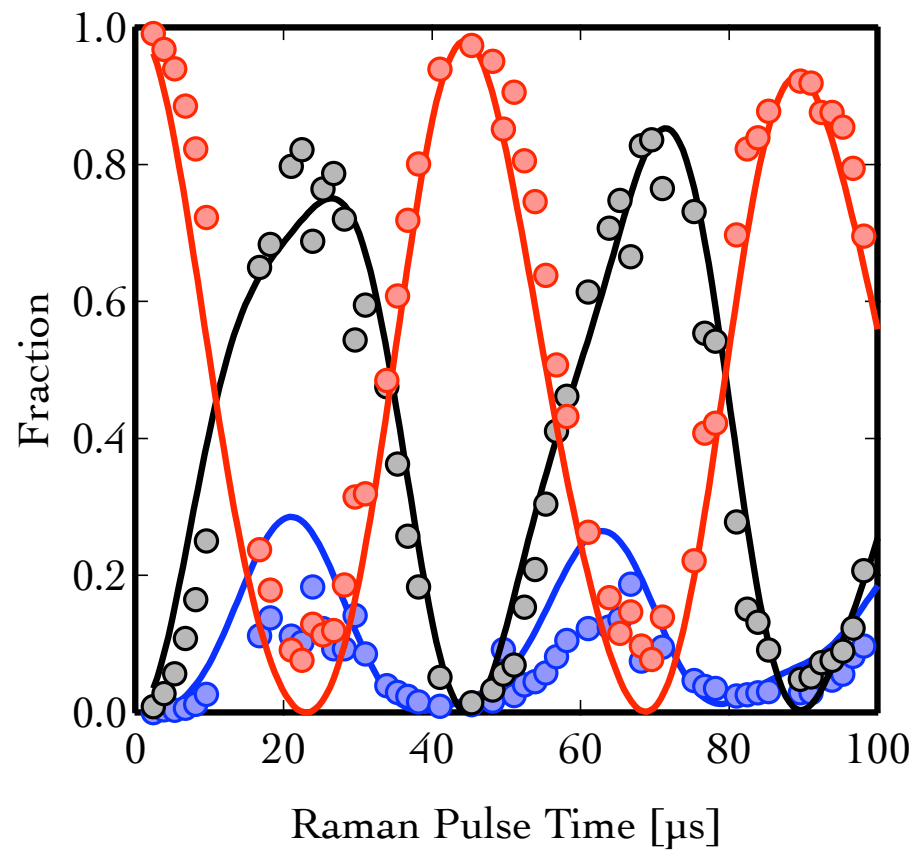
## References

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- [3] Günter et al, PRA **79** 011604 (2009)
- [4] IBS, PRA 063613 **79** (2009)

# Atom light interaction: pictures

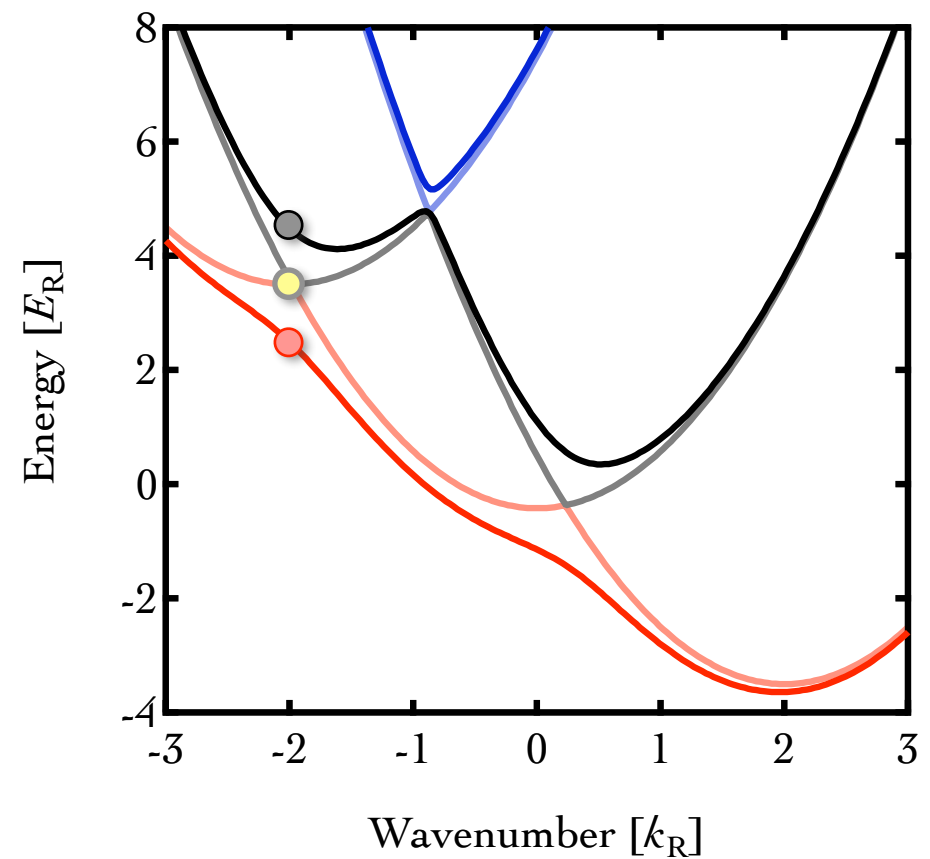
## Time evolution

In the sudden limit (Raman-Nath)  
Population oscillations yield coupling



## Coupled States

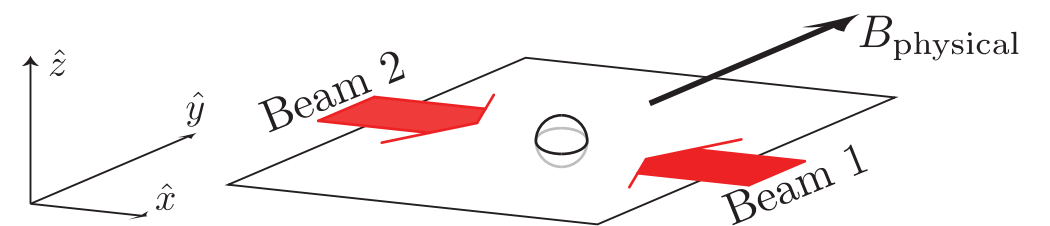
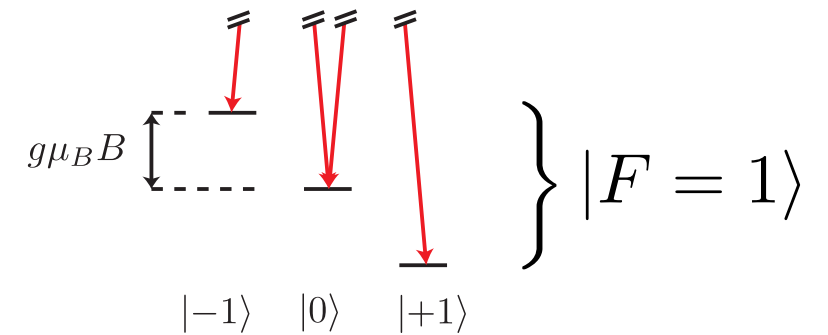
States will be labeled by:  
(1) a “band index” and by  
(2) a momentum  $k$



# Atom light interaction: vector potential

## Atom light interaction

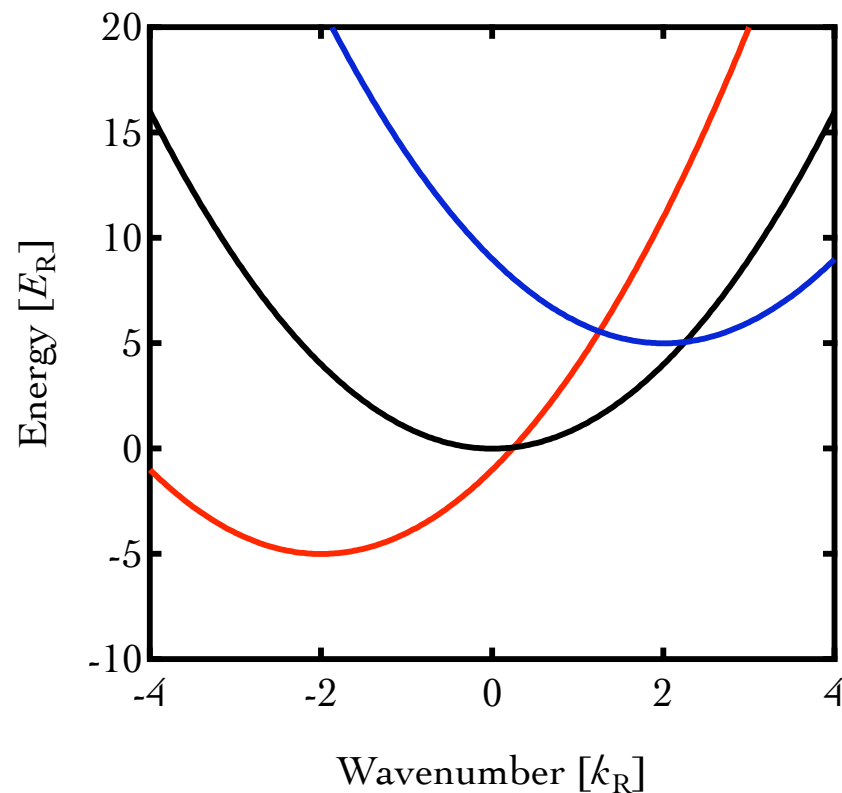
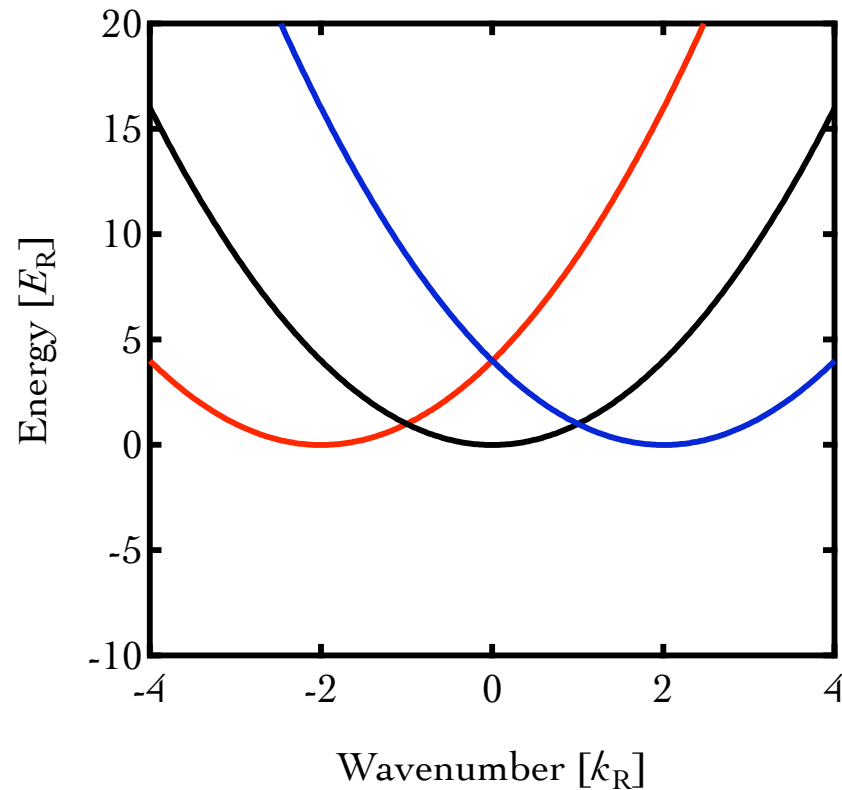
Given the following geometry and levels



## Dimensions

$$k_R = \frac{2\pi}{\lambda}, \quad E_R = \frac{\hbar^2 k_R^2}{2m}$$

$$E_R \approx h \times 3 \text{ kHz} = k_B \times 140 \text{ nK}$$



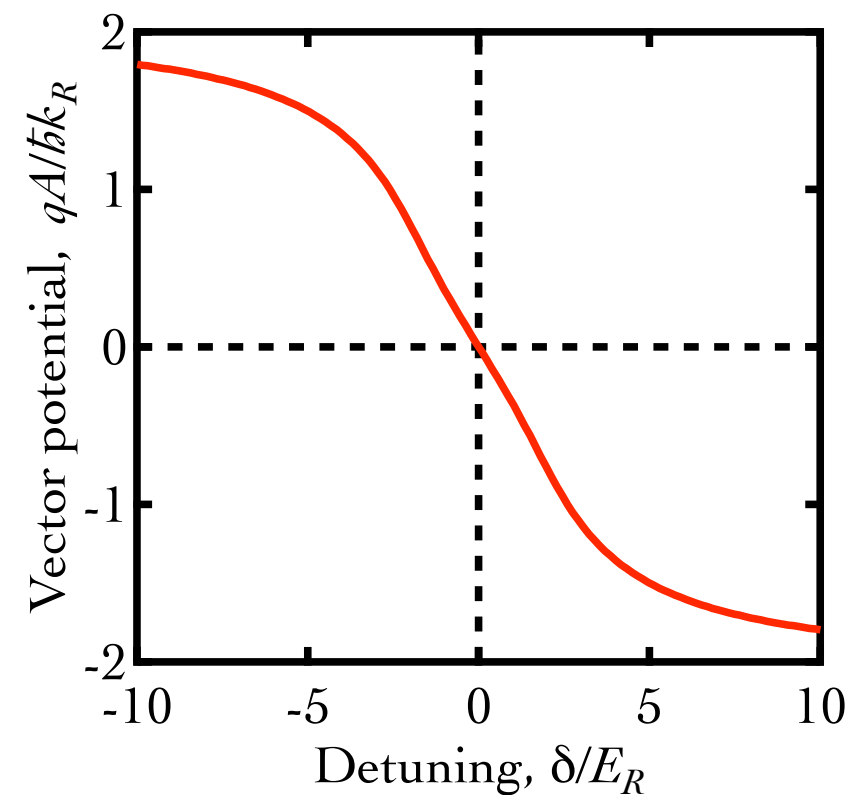
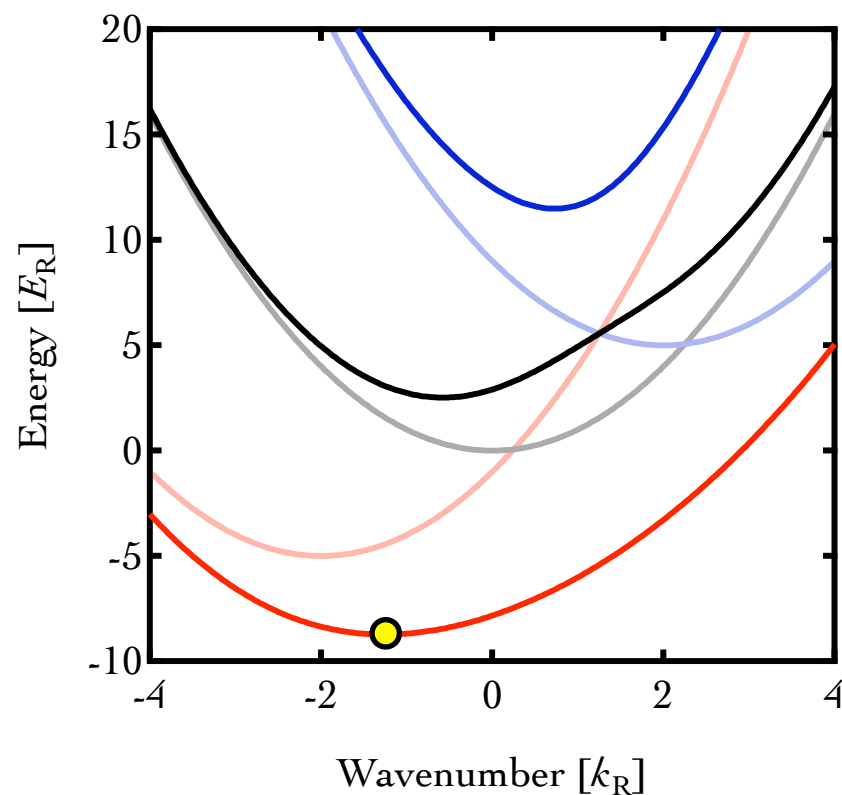
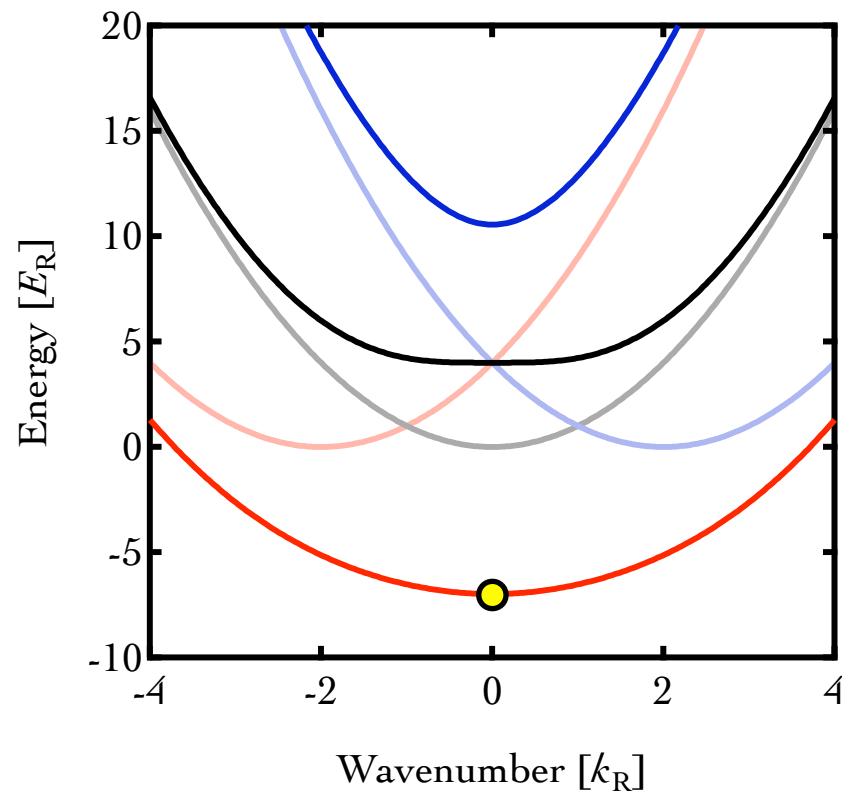
# Atom light interaction: vector potential

## Coupling Hamiltonian

$$H(k) = |\Psi(k)\rangle \begin{pmatrix} (\tilde{k}_x - 2)^2 + \delta & \Omega/2 & 0 \\ \Omega/2 & (\tilde{k}_x)^2 & \Omega/2 \\ 0 & \Omega/2 & (\tilde{k}_x + 2)^2 - \delta \end{pmatrix} \langle \Psi(k)|$$

## Engineered vector potential

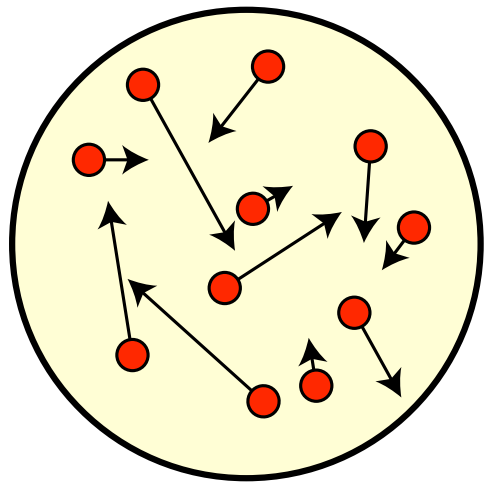
$$\hat{H} = \frac{\hbar^2}{2m} \left[ \left( k_x - \frac{qA_x}{\hbar} \right)^2 + \left( k_y - \frac{qA_y}{\hbar} \right)^2 \right] + V(\mathbf{x})$$



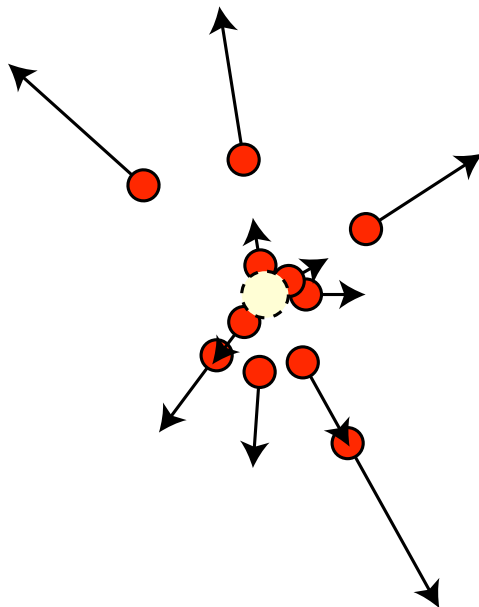
# Measurement: Time-of-flight and Stern-Gerlach

Camera's point of view

Before TOF

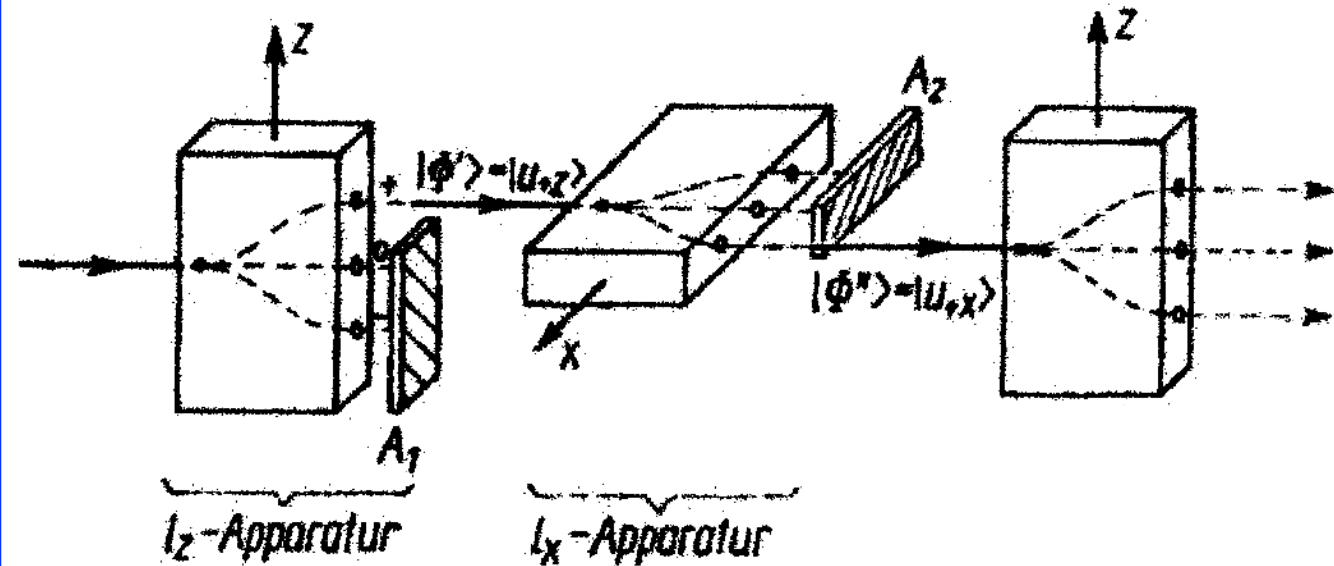


After TOF



Magnetic field gradient  $B_y = B' y$

Field gradient along the  $y$  direction

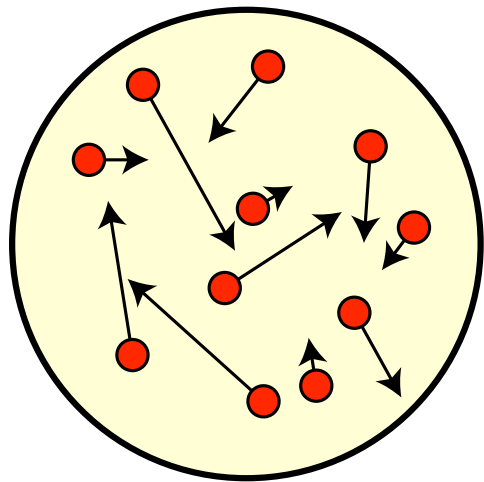


# Measurement: Time-of-flight and Stern-Gerlach

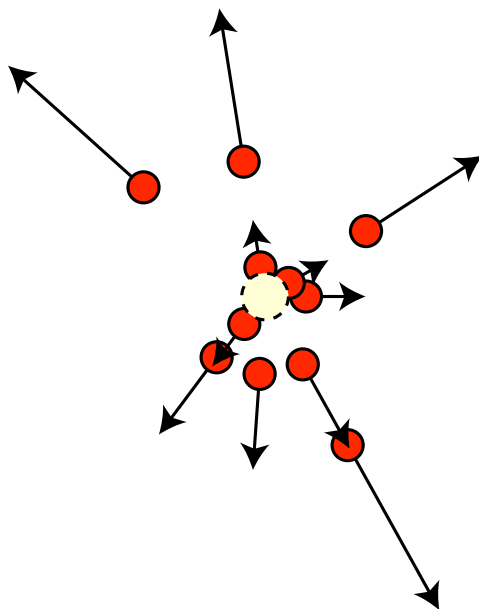
Camera's point of view

Field gradient along the  $y$  direction

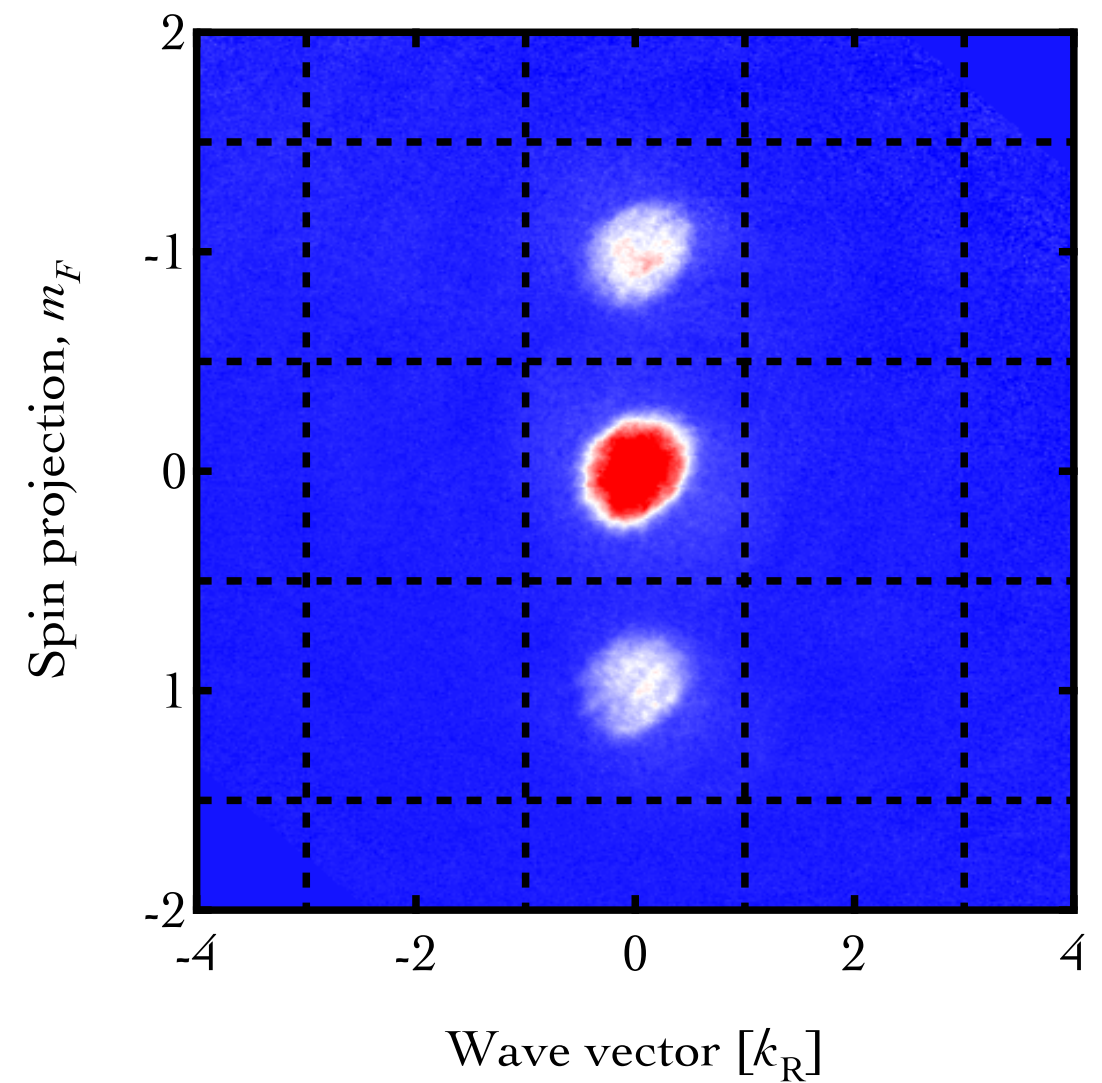
Before TOF



After TOF



Magnetic field gradient  $B_y = B' y$



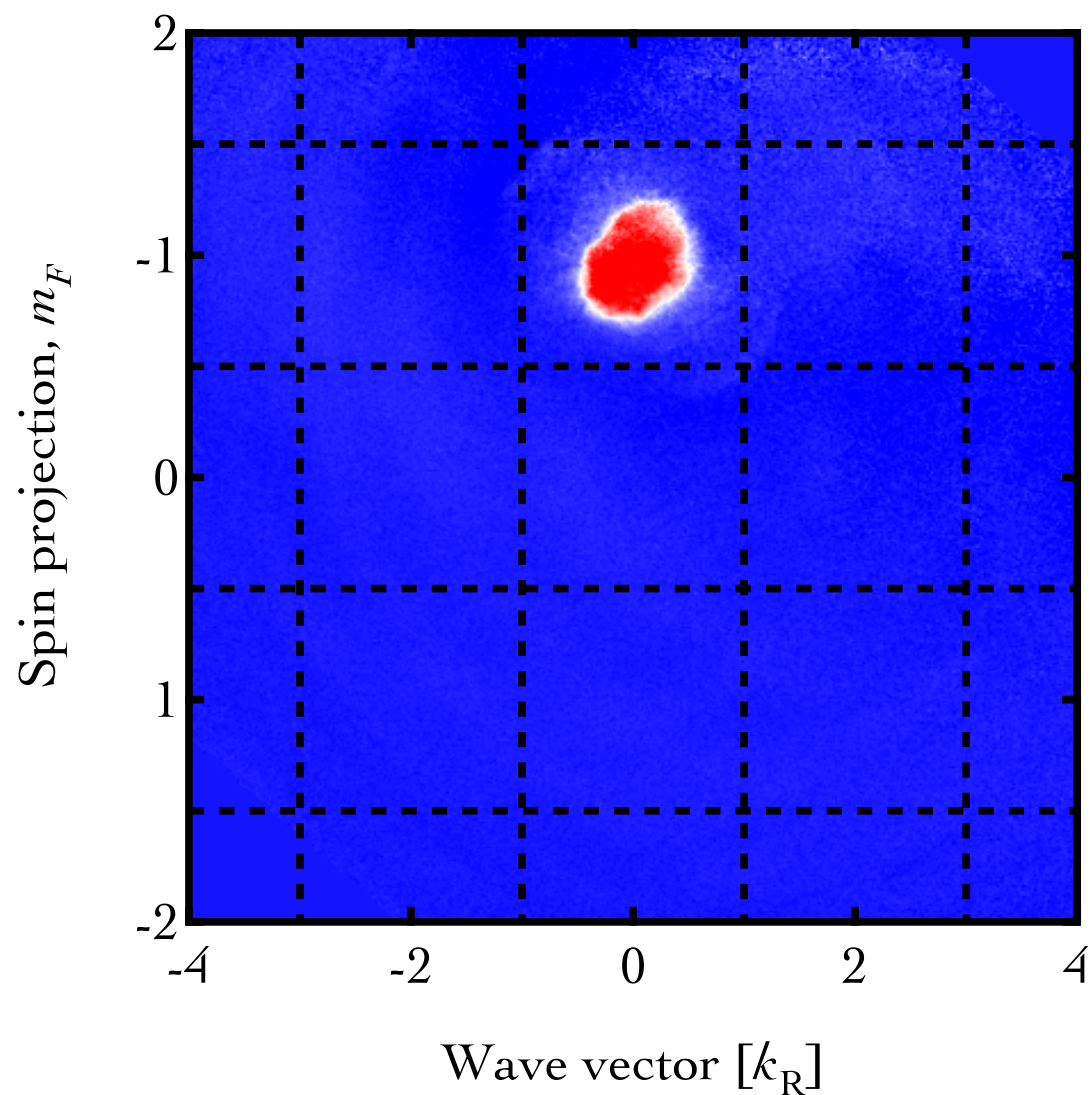
# In the lab

## Adiabatic manipulation of atoms

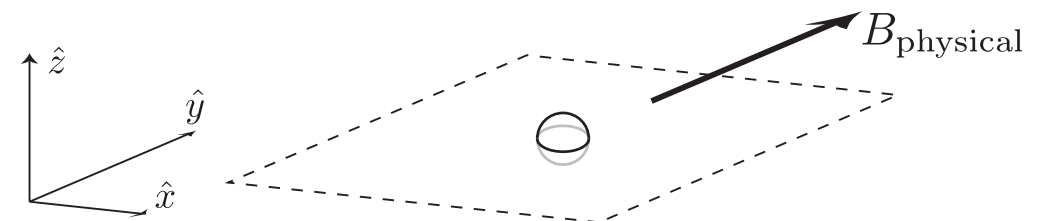
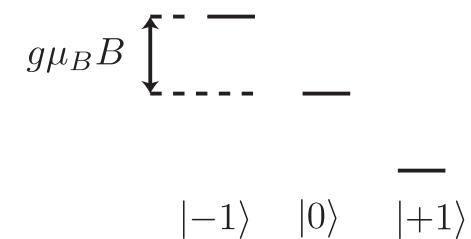
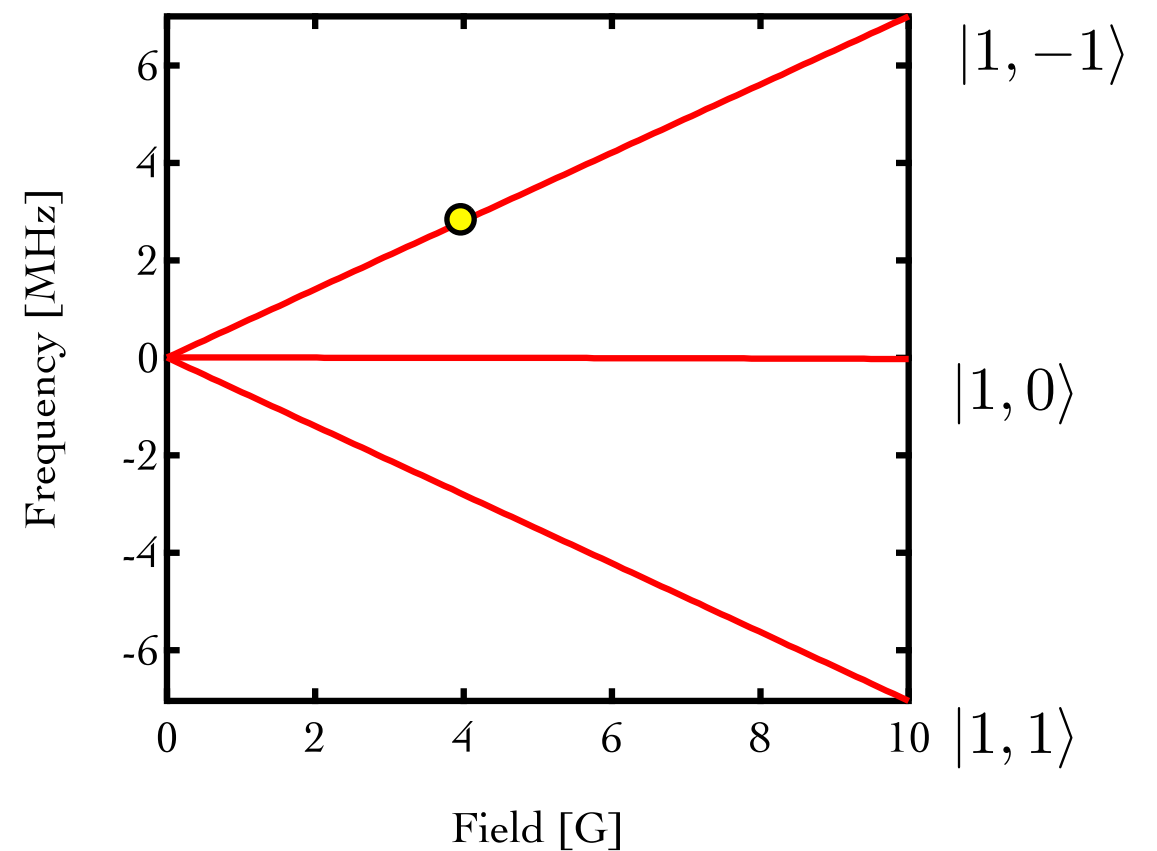
Initial state  $|F = 1, m_F = -1\rangle$

Suddenly turn off dipole trap, then TOF

$B$  field gradient



## Zeeman shift



# Loading: momentum

## Adiabatic manipulation of atoms

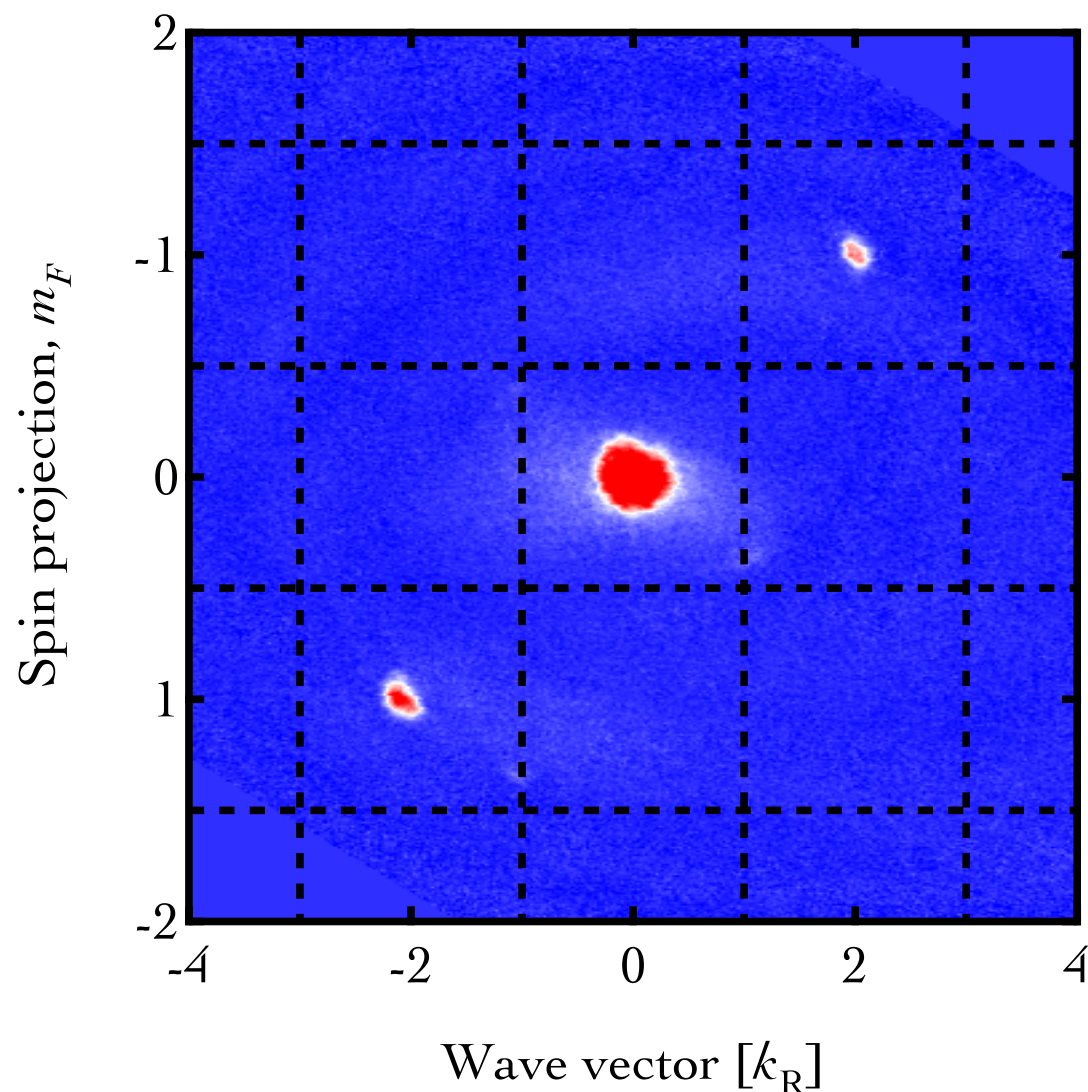
Initial state  $|F = 1, m_F = -1\rangle$

RF dressed state (RF on, ramp  $B$  to resonance)

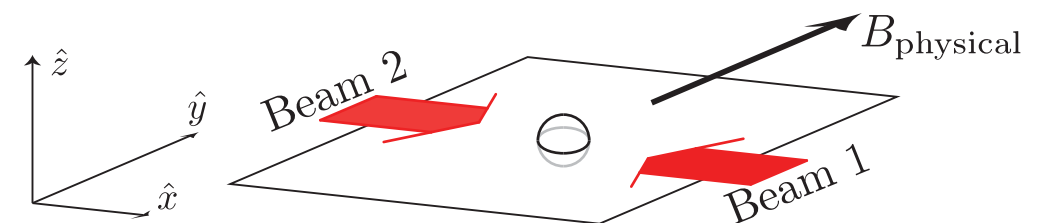
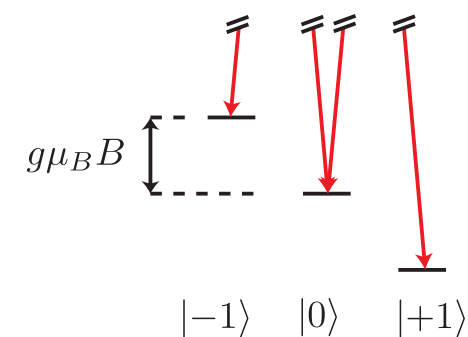
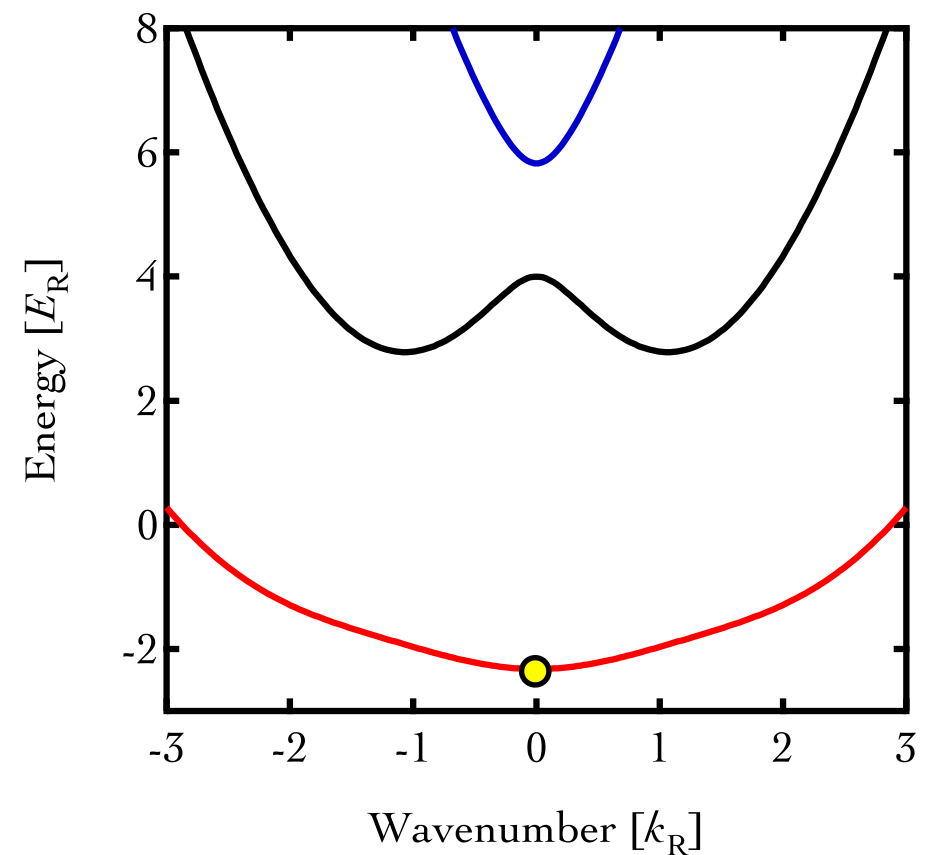
Raman + RF dressed state (Ramp Raman on)

Raman only dressed state (Ramp RF off)

Suddenly turn off Raman + dipole trap, TOF



## Raman Dressed

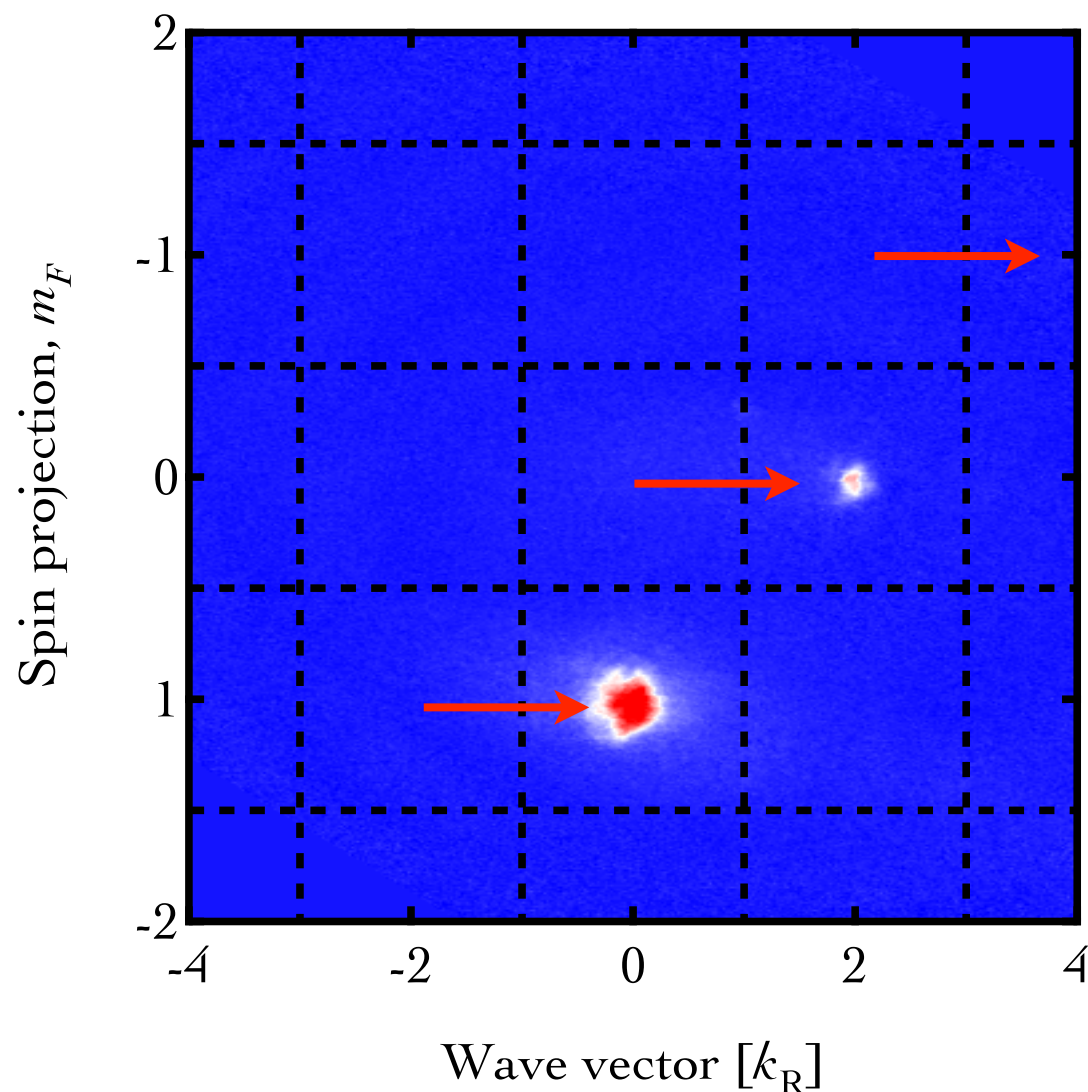


# Displaced momentum distribution

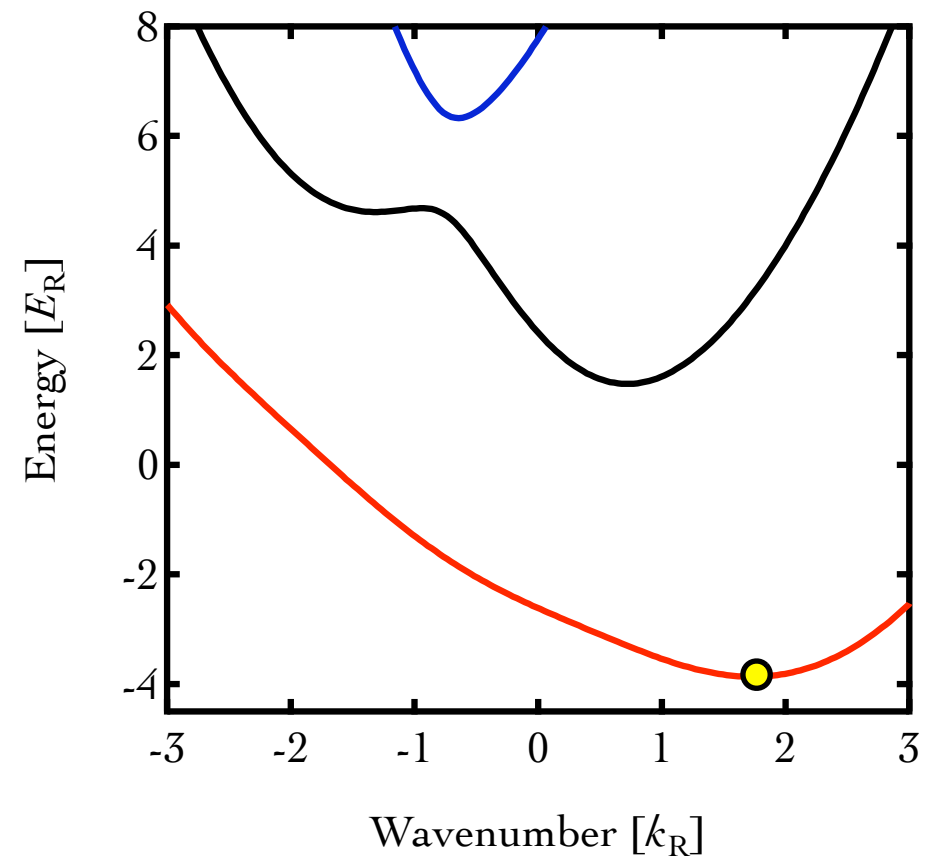
## Conserved

Abrupt turnoff conserves mechanical velocity

Mechanical velocity is averaged over all orders and is zero in equilibrium (of course).



## Raman Dressed



## 1. Junior mechanics

Canonical variables and vector potential

$$H = \frac{(\mathbf{p} - q\mathbf{A})^2}{2m}$$

$$\dot{p}_j = -\frac{\partial}{\partial x_i} H, \quad \dot{x}_j = \frac{\partial}{\partial p_i} H$$

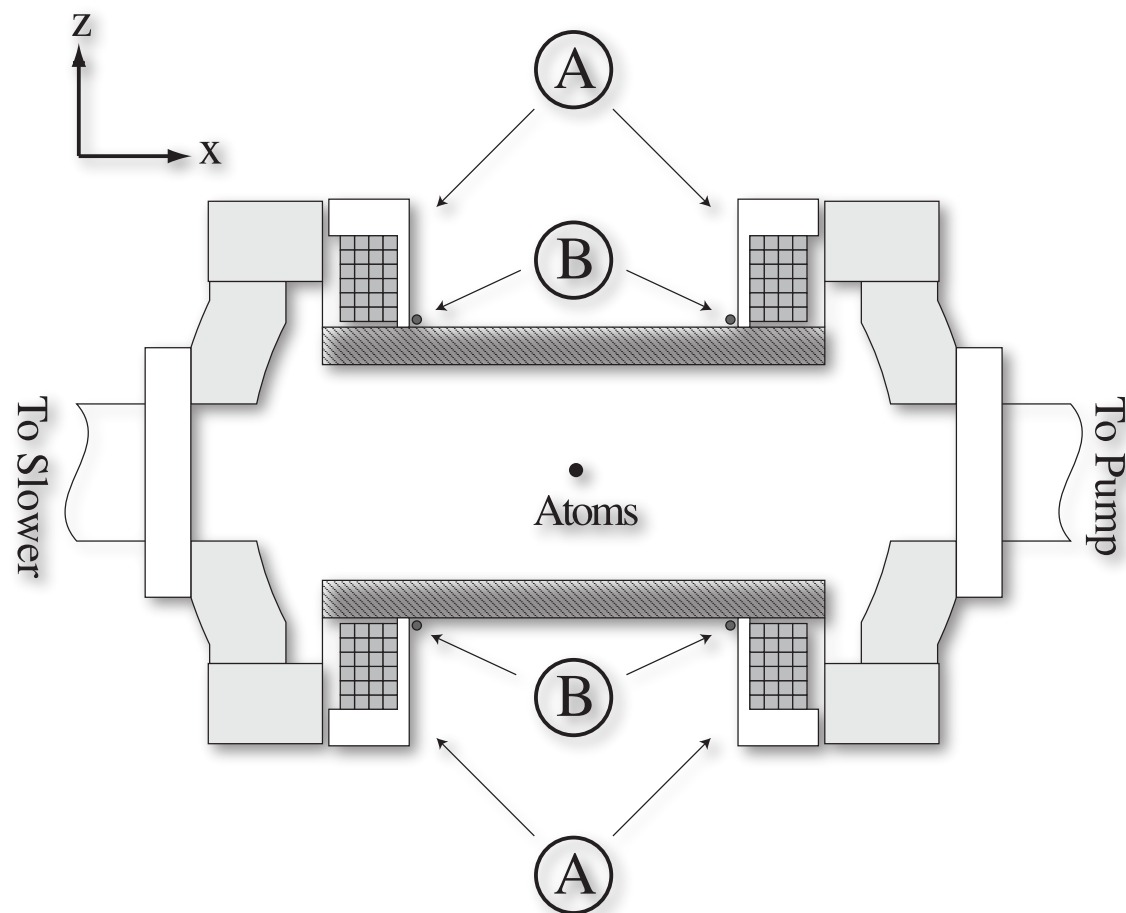
$$\dot{x}_j = v_j = \frac{p - qA_j}{m}$$

# A laboratory tunable vector potential

## Idea

We can control the *engineered* vector potential in time and space giving *synthetic*  $\mathbf{E}$  and  $\mathbf{B}$  fields.

Bias and quadrupole  $\mathbf{B}$  fields = offset and gradient in detuning.

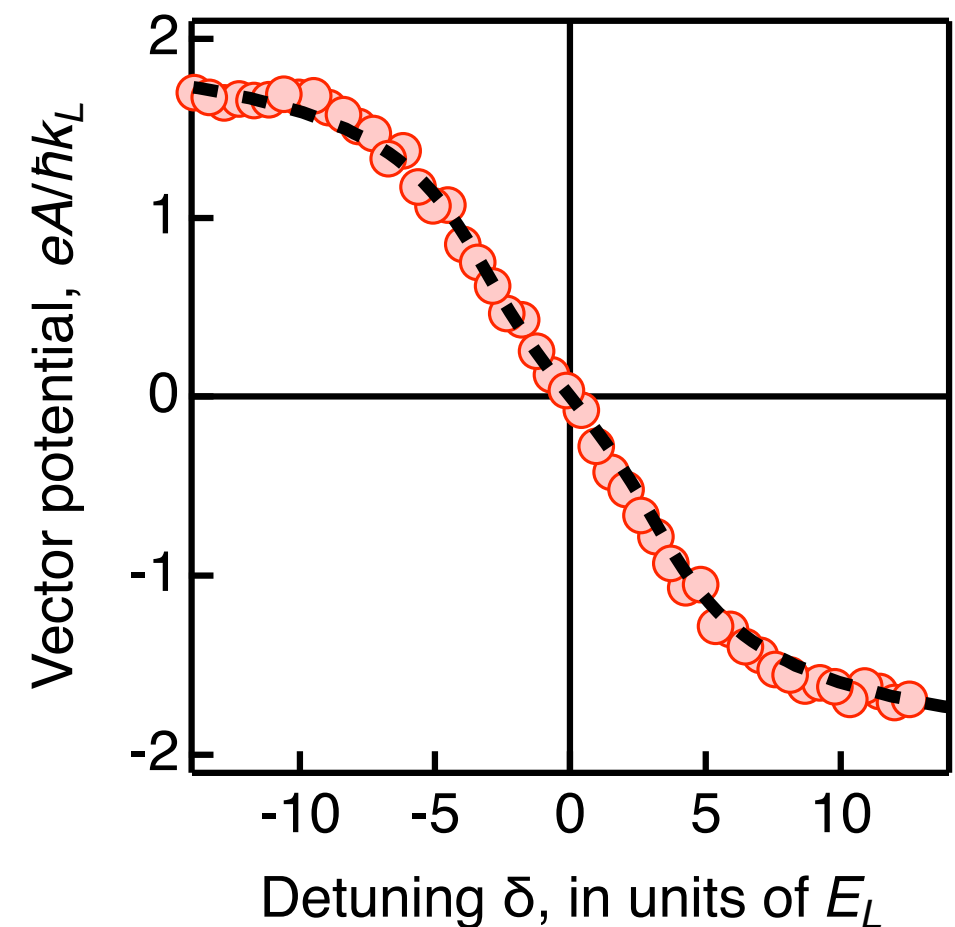


## Transfer function

$$\hat{H} = \frac{\hbar^2}{2m} \left\{ \left[ k_x - \frac{qA_x(\delta, \Omega)}{\hbar} \right]^2 + k_y^2 \right\} + V(\mathbf{x})$$

where  $\delta(x, y, t)$  and  $\Omega(x, y, t)$

The detuning and coupling specify the local synthetic vector potential



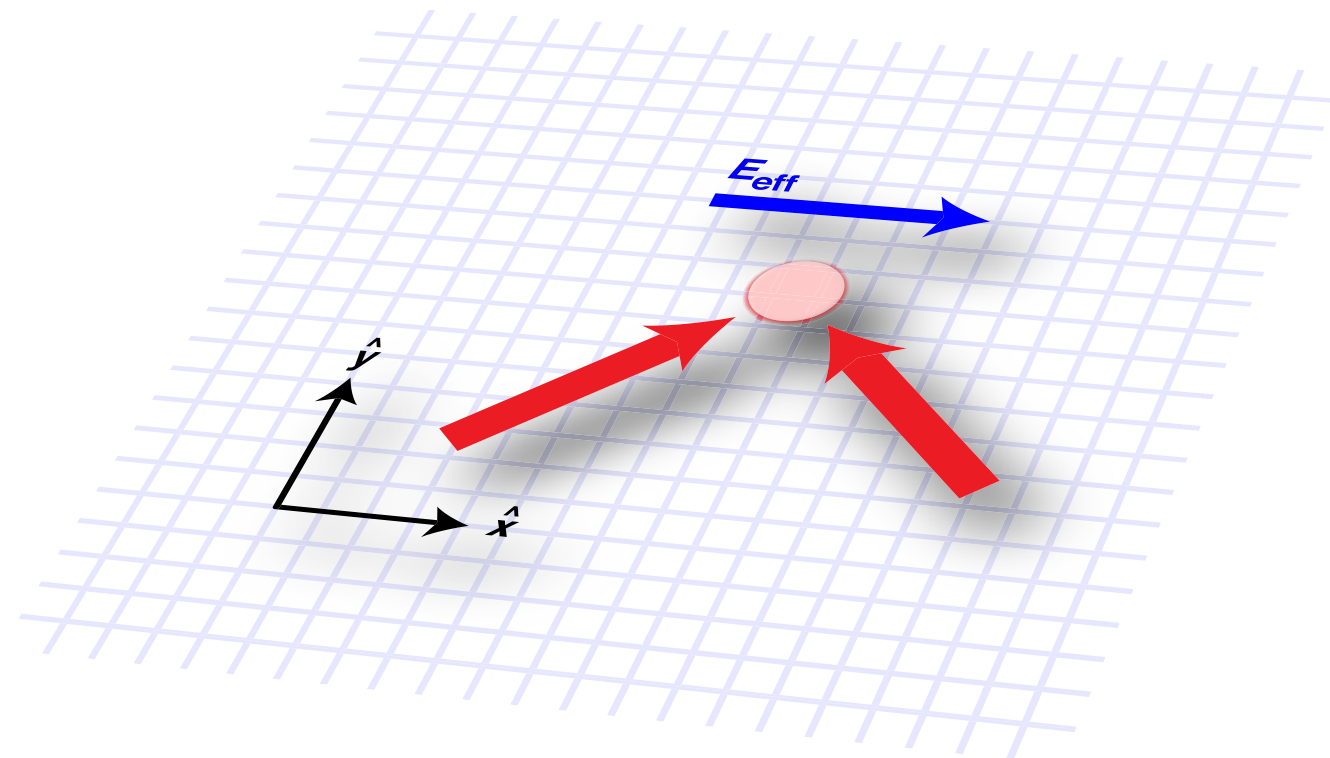
## References

- [1] Y.-J. Lin et al, PRA **79** 063631 (2009)

# Electric fields: time dependence

## Complete disclosure

Our beams now intersect at 90°  
Not for physics reasons.

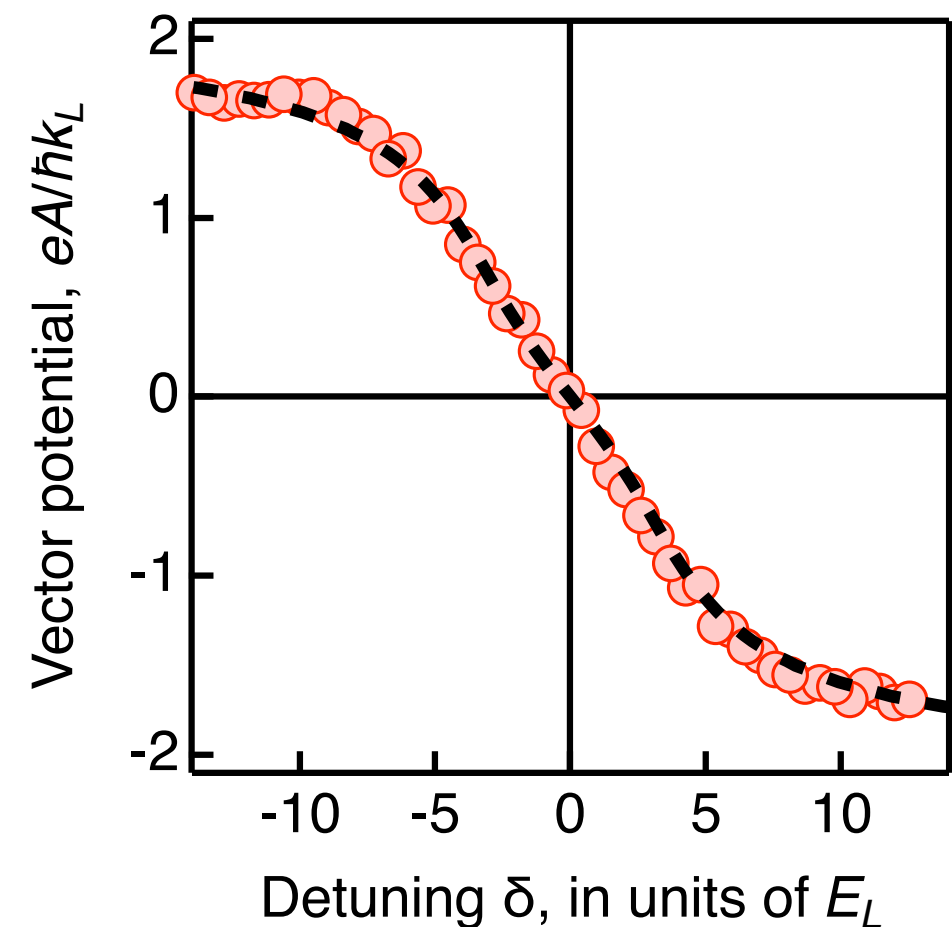


## Transfer function

$$\hat{H} = \frac{\hbar^2}{2m} \left\{ \left[ k_x - \frac{qA_x(\delta, \Omega)}{\hbar} \right]^2 + k_y^2 \right\} + V(\mathbf{x})$$

where  $\delta(x, y, t)$  and  $\Omega(x, y, t)$

The detuning and coupling specify the local synthetic vector potential



# Synthetic Electric Field

## A uniform vector potential: forces

Time dependence gives electric fields and forces  
Usual “quasi-static assumptions”

### 1. Freshman version

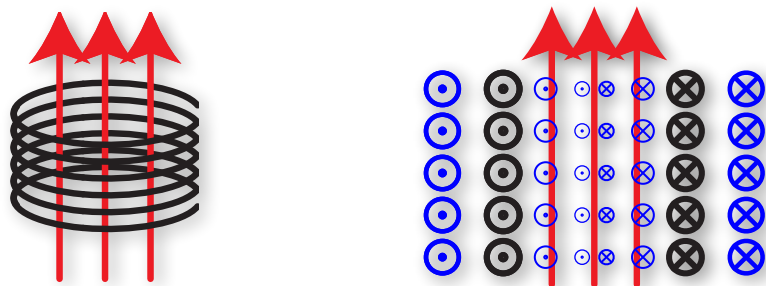
$$\mathbf{E} = -\nabla\Phi - \frac{\partial\mathbf{A}}{\partial t}$$

$$\frac{m\Delta\dot{\mathbf{x}}}{\hbar} = \frac{e}{\hbar} \int \mathbf{E} dt = -\frac{e}{\hbar} \Delta\mathbf{A}$$

### 2. Junior version

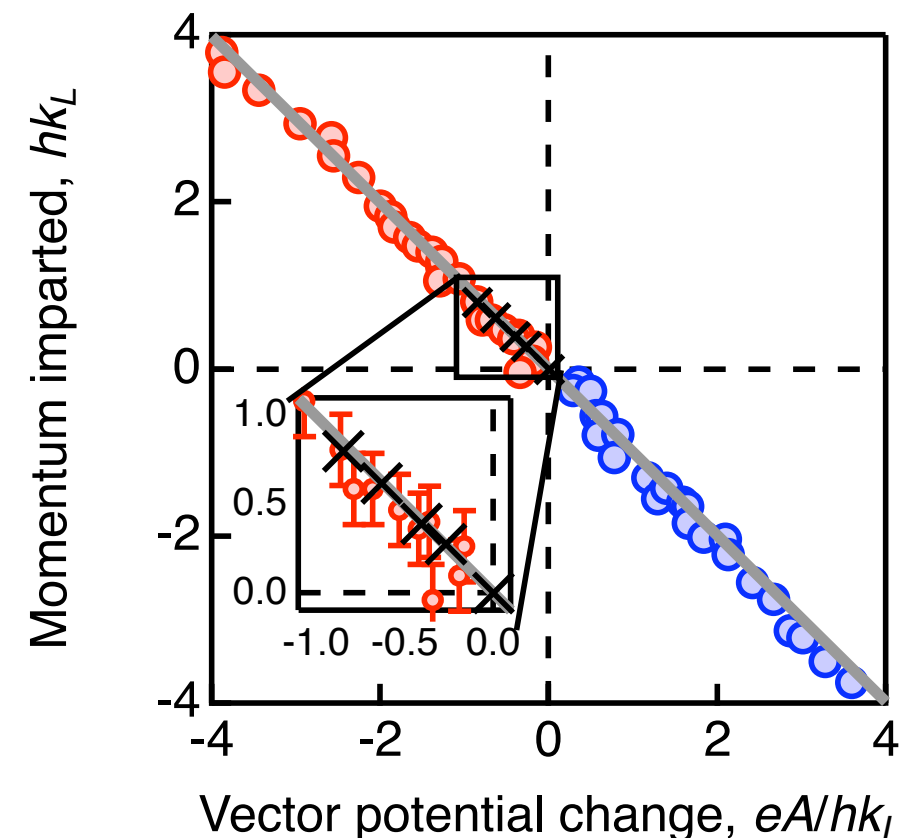
$$\frac{m\dot{x}_j}{\hbar} = k_j - \frac{qA_j}{\hbar}, \quad \dot{k}_j = -\frac{1}{\hbar} \frac{\partial}{\partial x_i} H = 0$$

### Geometric example



## Realization with dressed states

Yes! Atoms acquire expected  $-2 k_R$  mechanical momentum kick.



Our synthetic vector potential behaves just like the real thing

### References

Y.-J. Lin et al Nat. Phys. (2011)

# Synthetic magnetic field

## Loading procedure

Initial state

RF dressed state (RF on, ramp  $B$  to resonance)

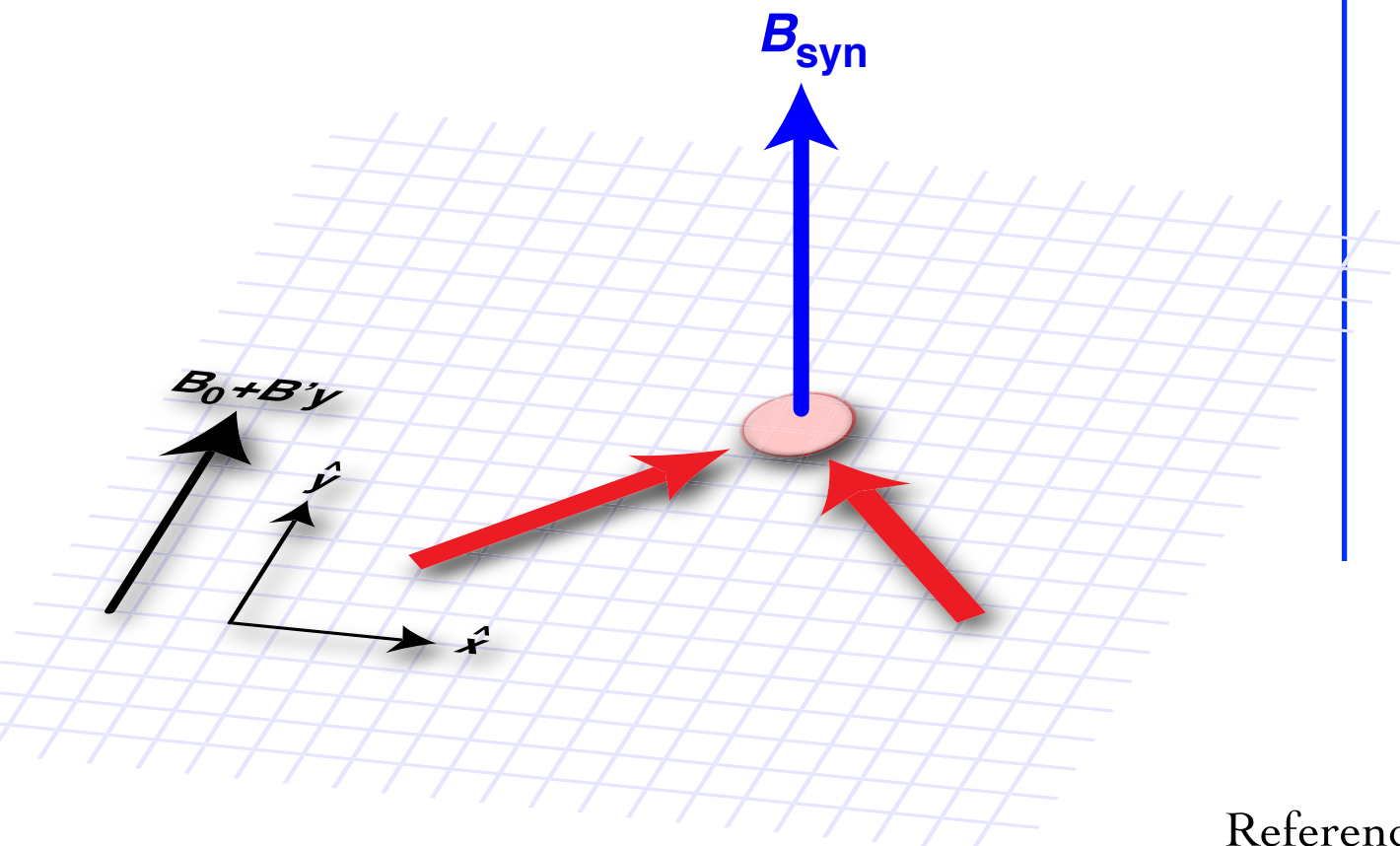
Raman + RF dressed state (Ramp Raman on)

Raman only dressed state (Ramp RF off)

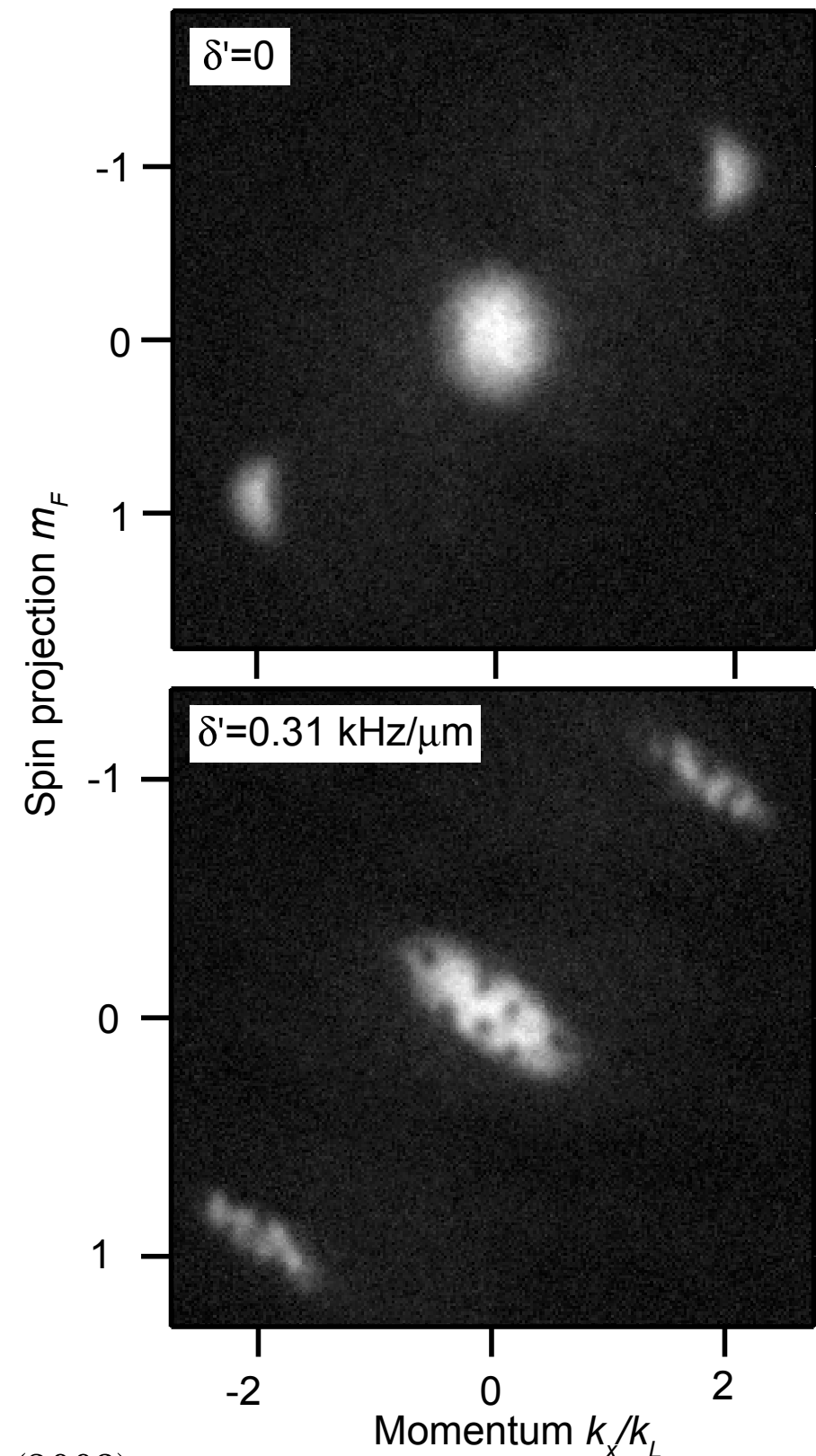
Ramp field gradient on (from 0 to 500 Hz/ $\mu\text{m}$ )

Equilibrate for 500 ms

TOF imaging



## Outcome



## References

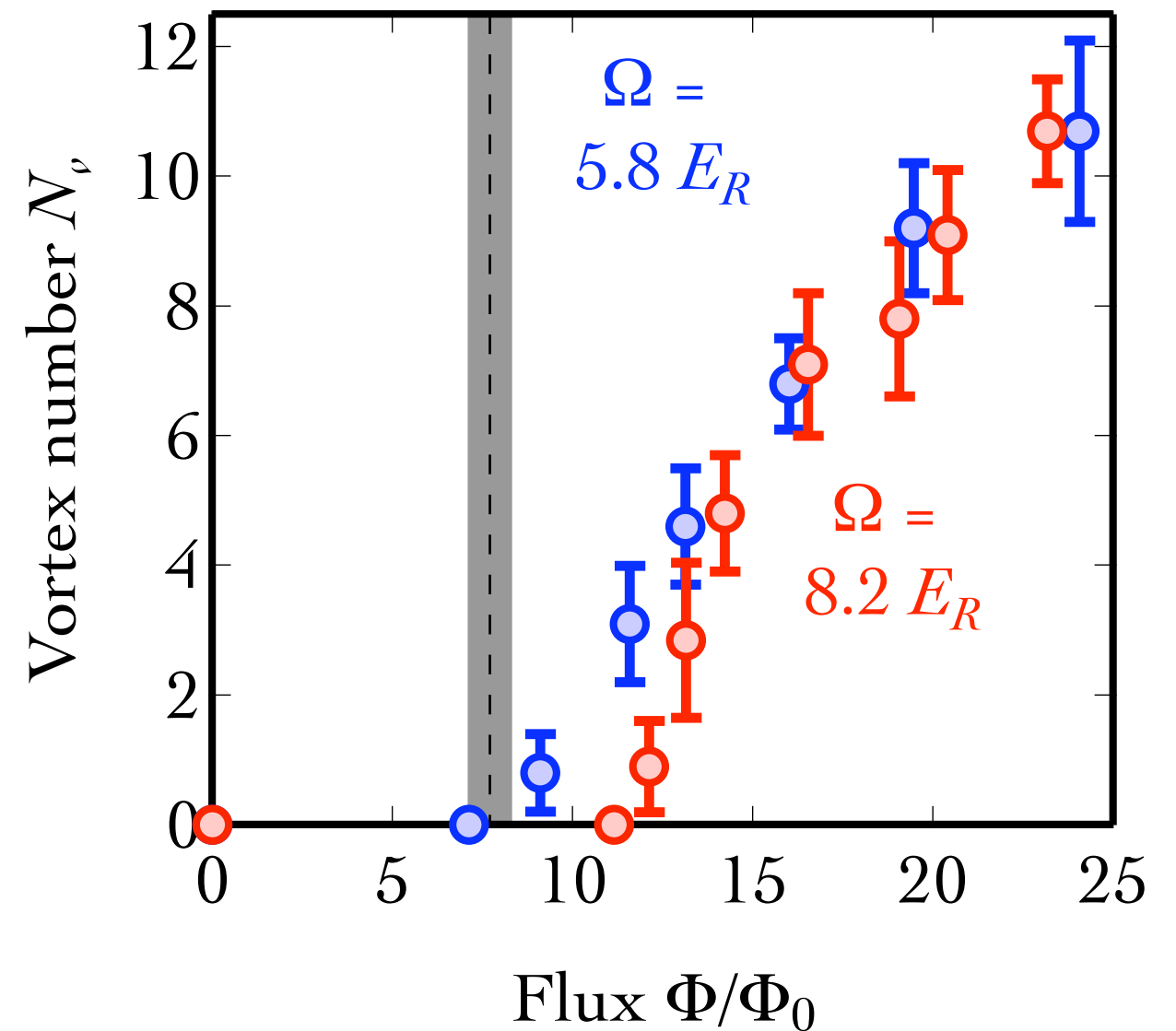
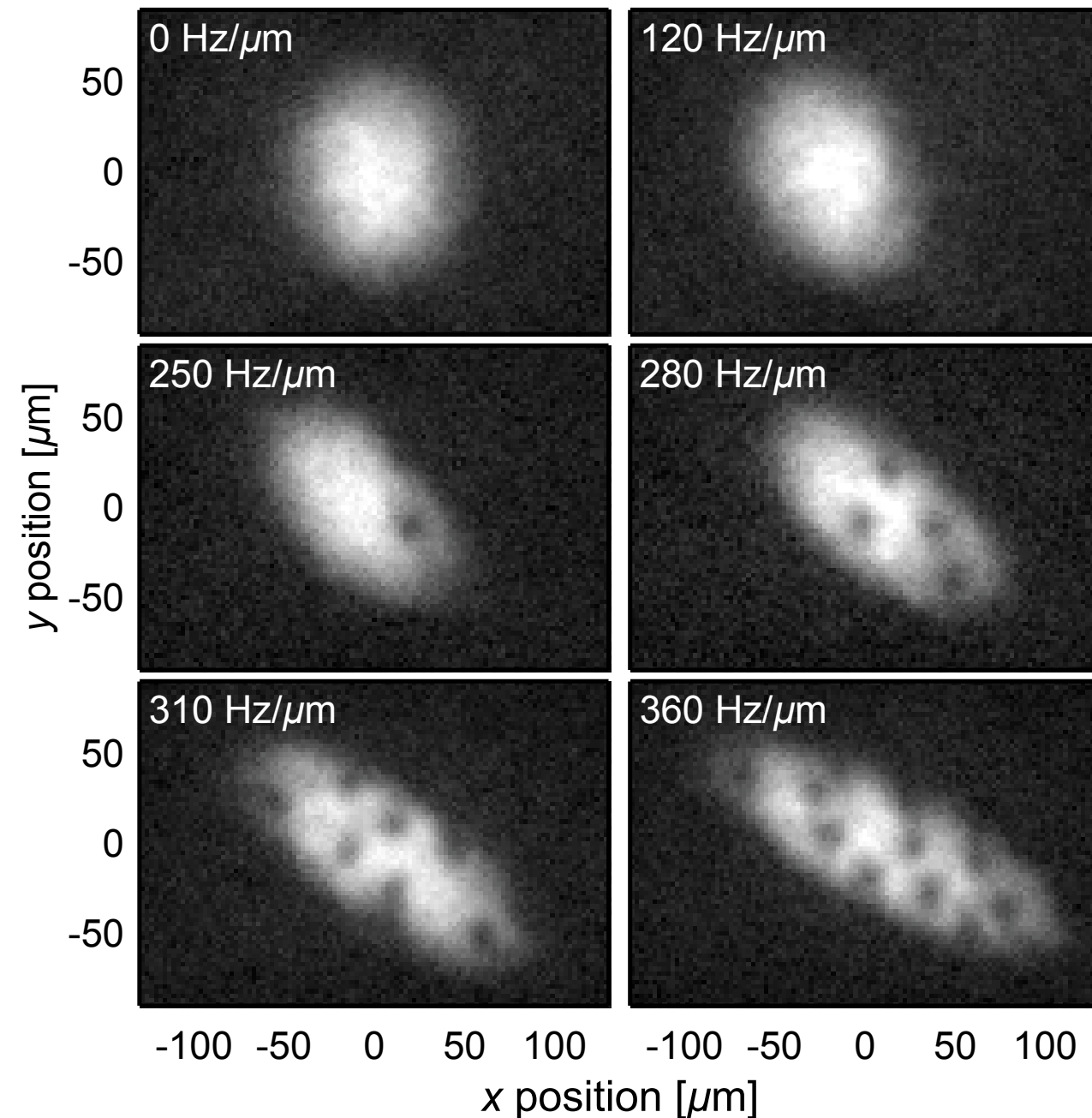
Y.-J. Lin *et al* Nature (2009)

# But that not what happened...

## Vortex number

## Critical field for vortex formation

Spatial dependence gives magnetic fields and forces



## References

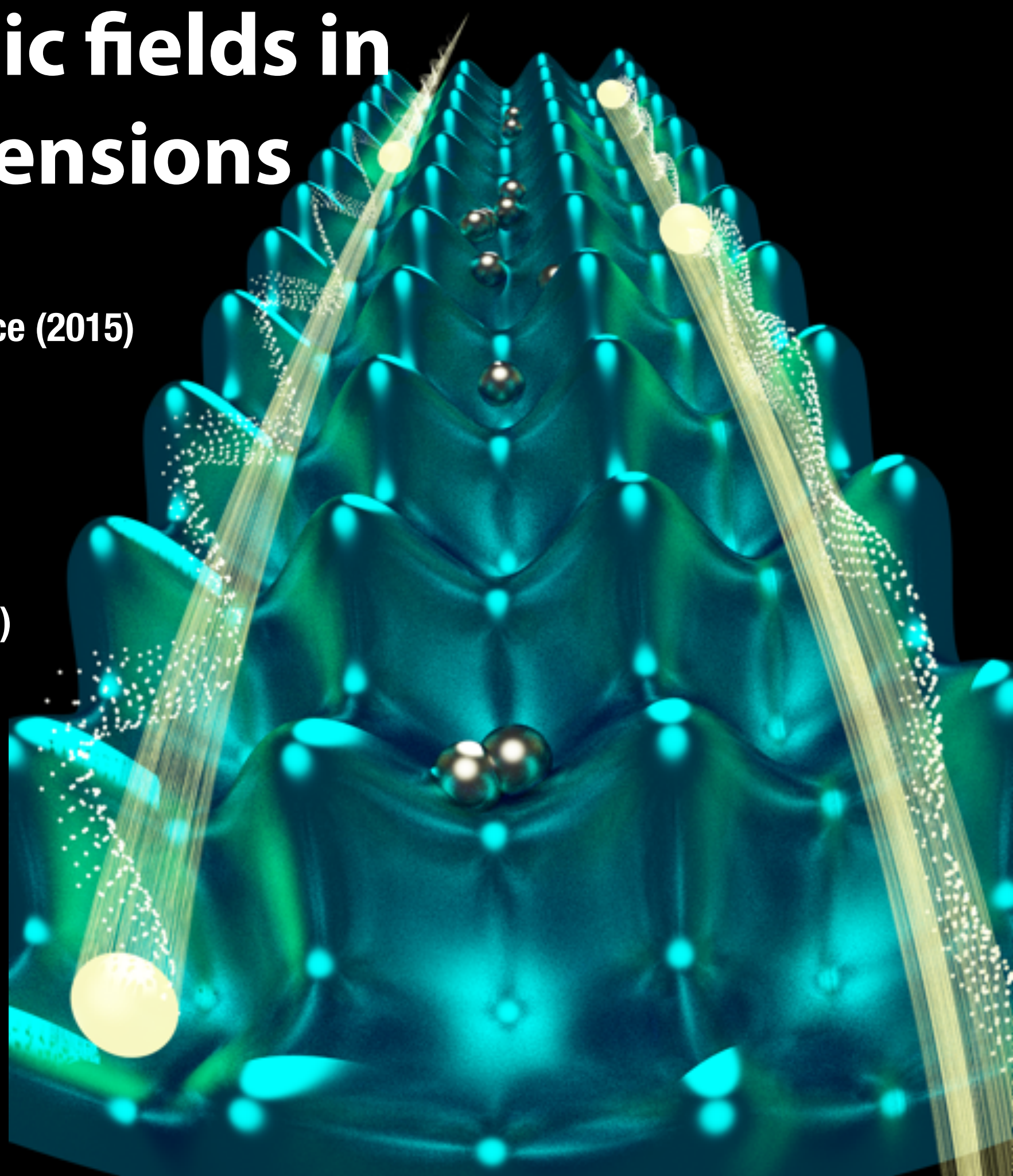
Extensive review: A.L. Fetter, RMP **81** 647 (2009)

# Large magnetic fields in synthetic dimensions

JQI:  
B. Stuhl and Hsin-I Lu, et al. Science (2015)

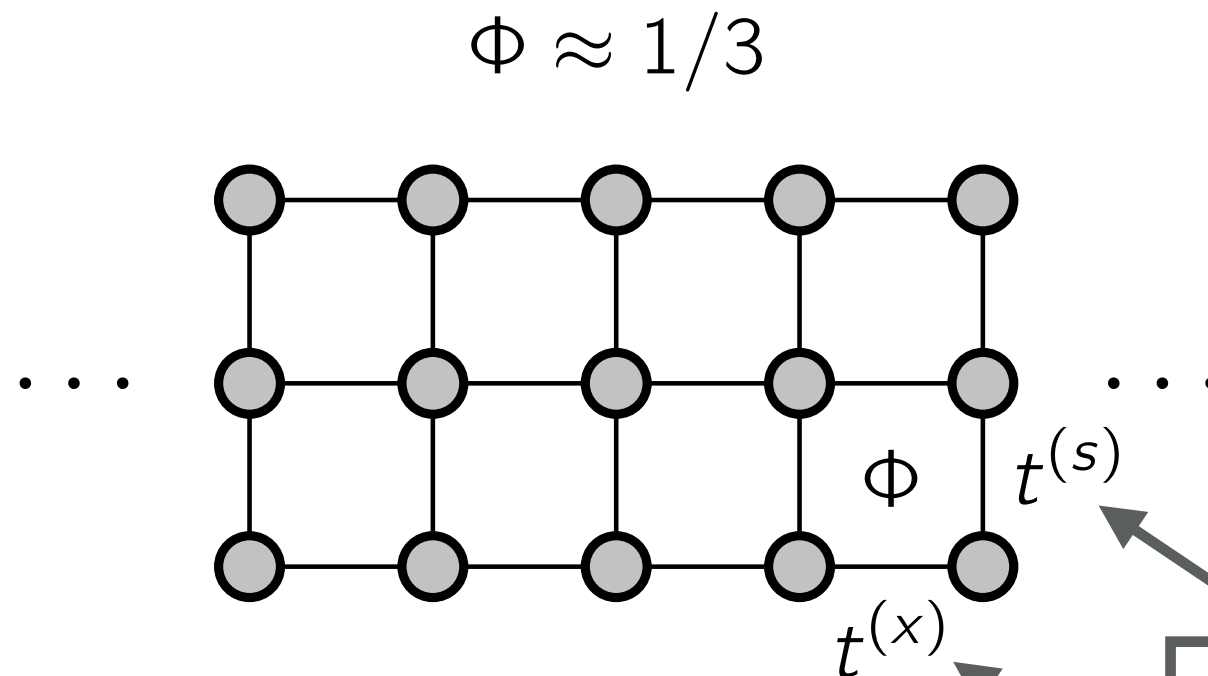
Florence  
M. Mancini et al. Science (2015)

THEORY PROPOSAL:  
Celi, A. et al. Phys. Rev. Lett. (2014)



# Where we are going:

## Large magnetic fields in a 2D lattice



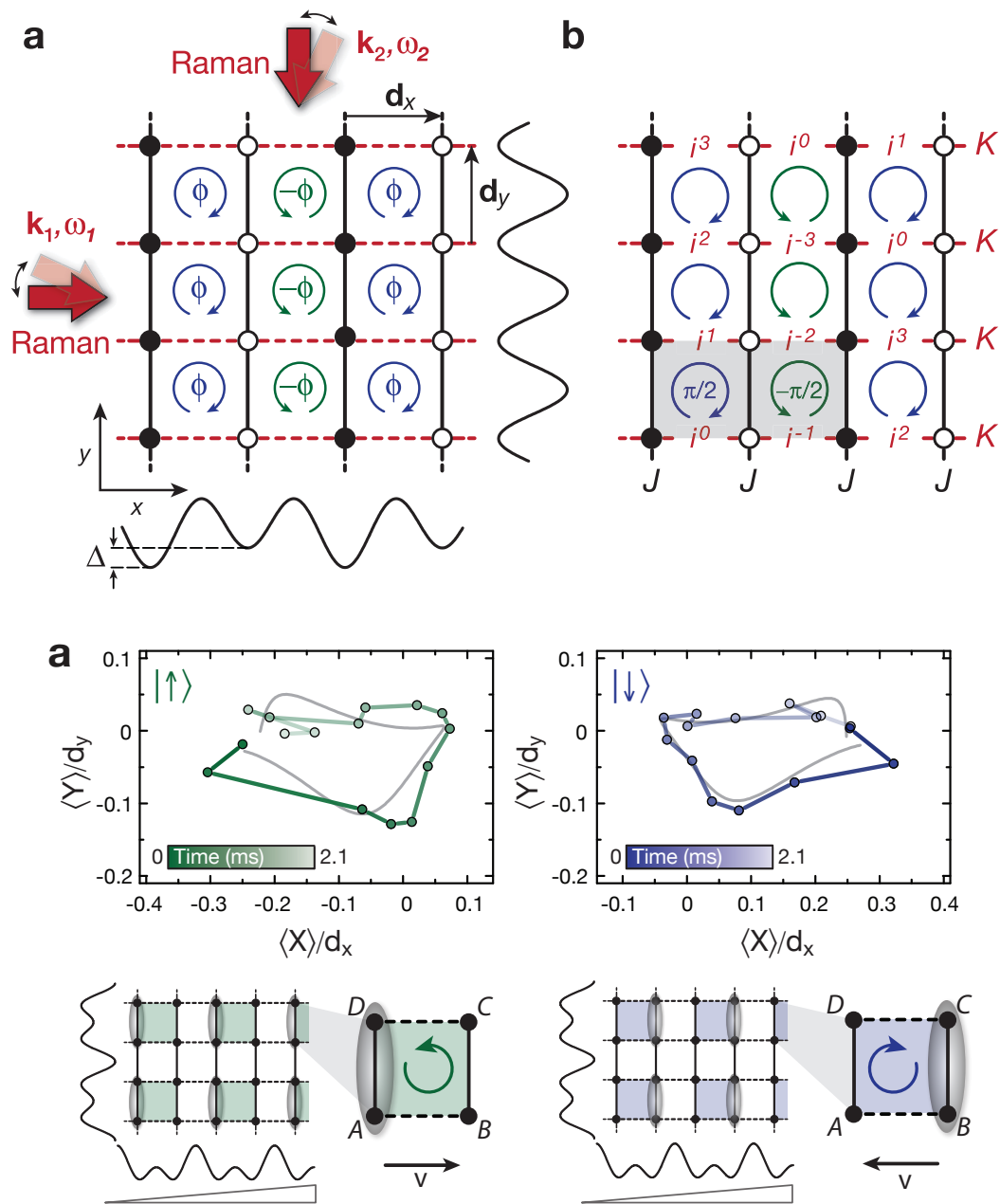
Tunneling also gives phases such that the acquired phase gives an effective Aharonov-Bohm phase

## References

B. Stuhl, et al. *Science* (2015); Celi, A. et al. *Phys. Rev. Lett.* (2014);

# AMO: fields in lattices

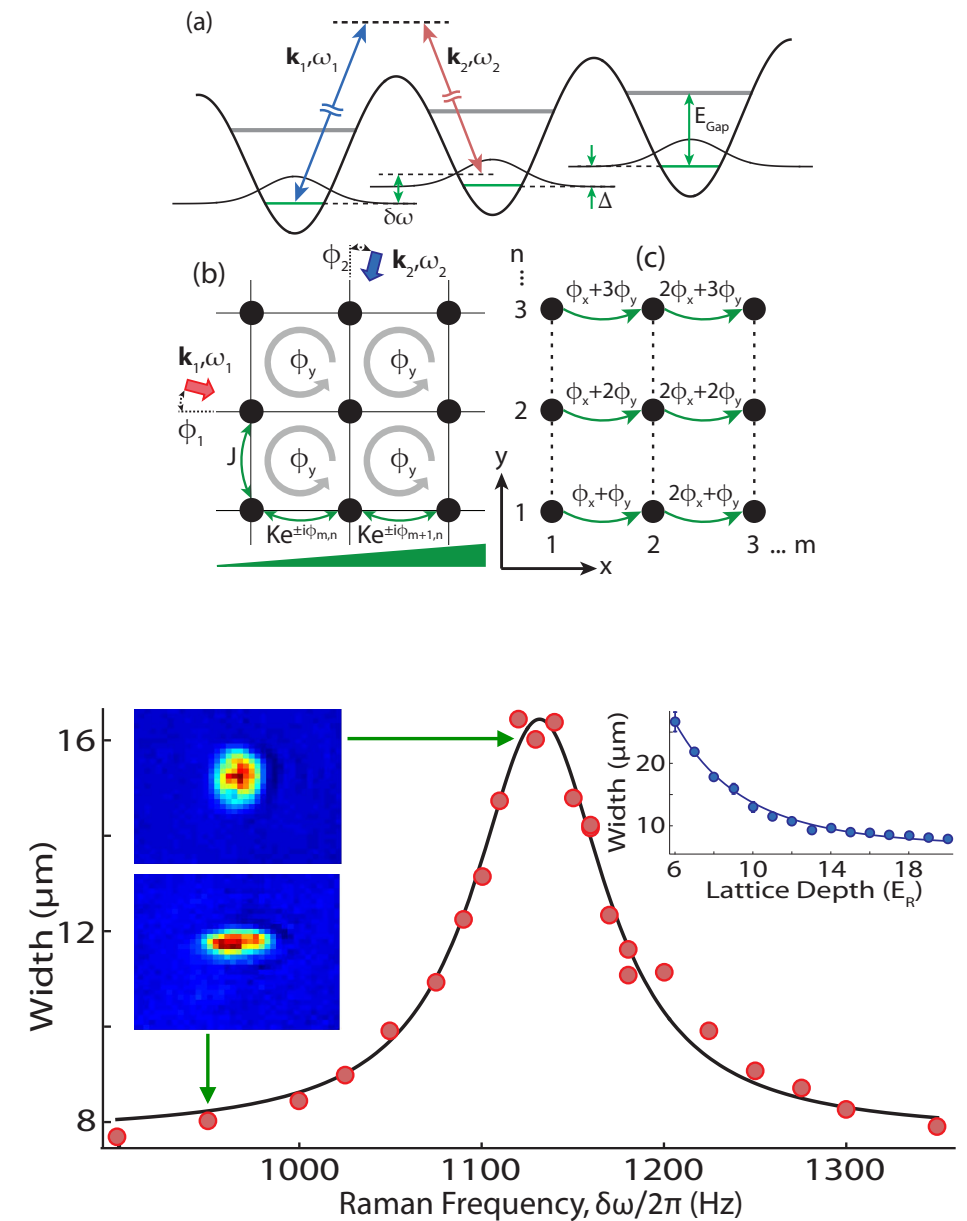
## Light assisted hopping I: Munich



## References

M. Aidelsburger *et al* PRL (2011), M. Aidelsburger *et al* PRL (2013)

## Light assisted hopping II: MIT

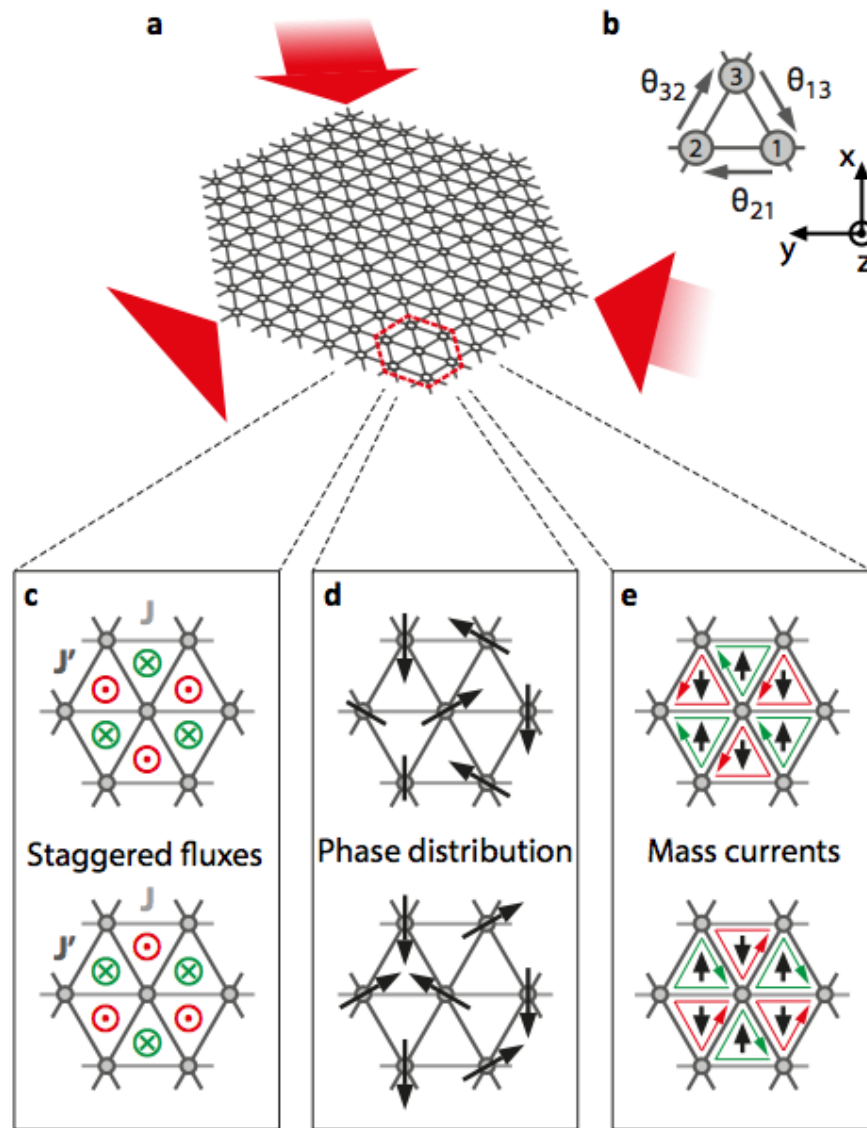


## References

C. J. Kennedy, *et al* Nat. Phys (2015), H. Miyake *et al* PRL (2013)

# AMO: exotic lattices

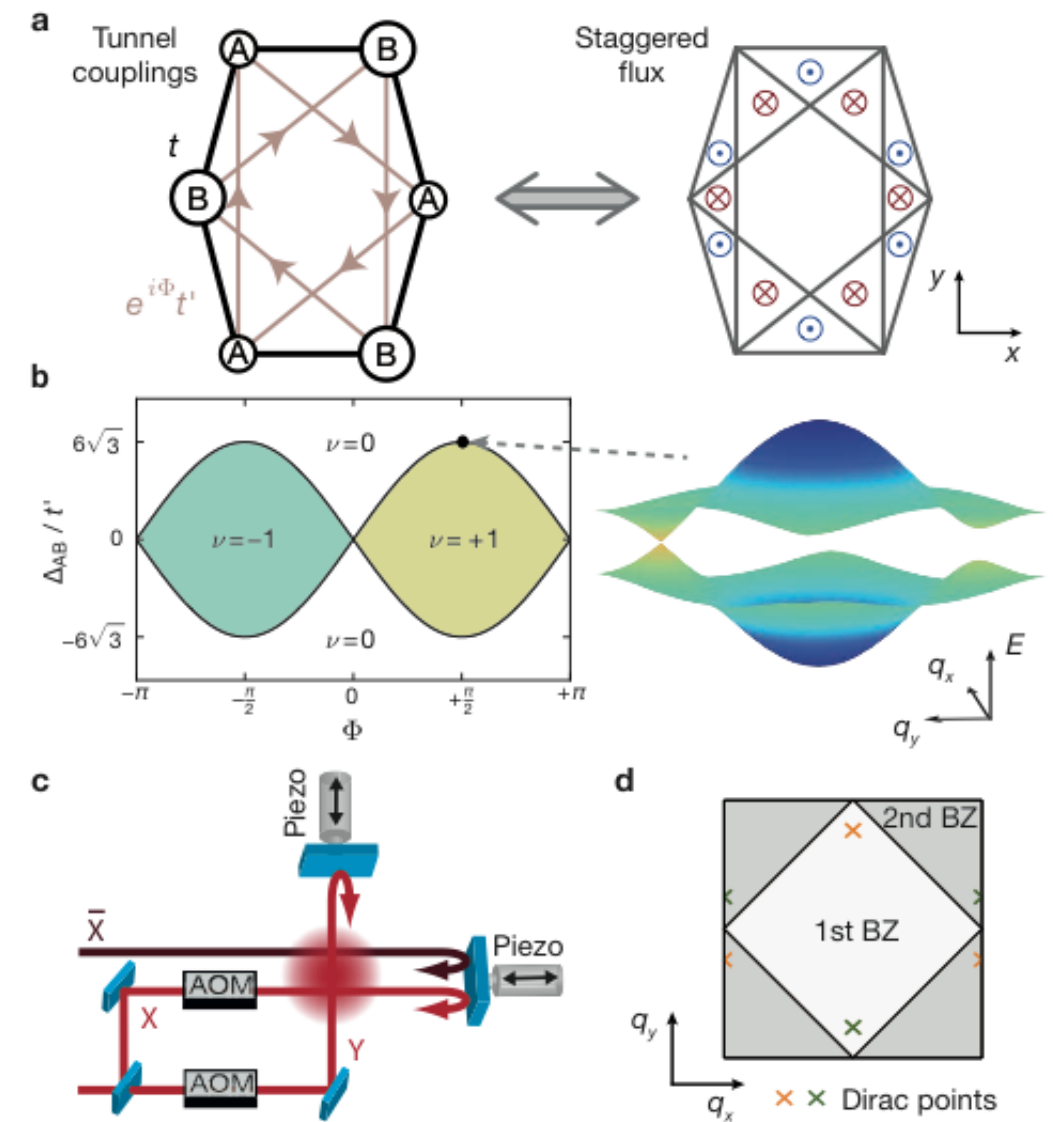
## Modulation I: Hamburg



## References

J. Struck *et al* N. Physics (2013)

## Modulation II: Zurich



## References

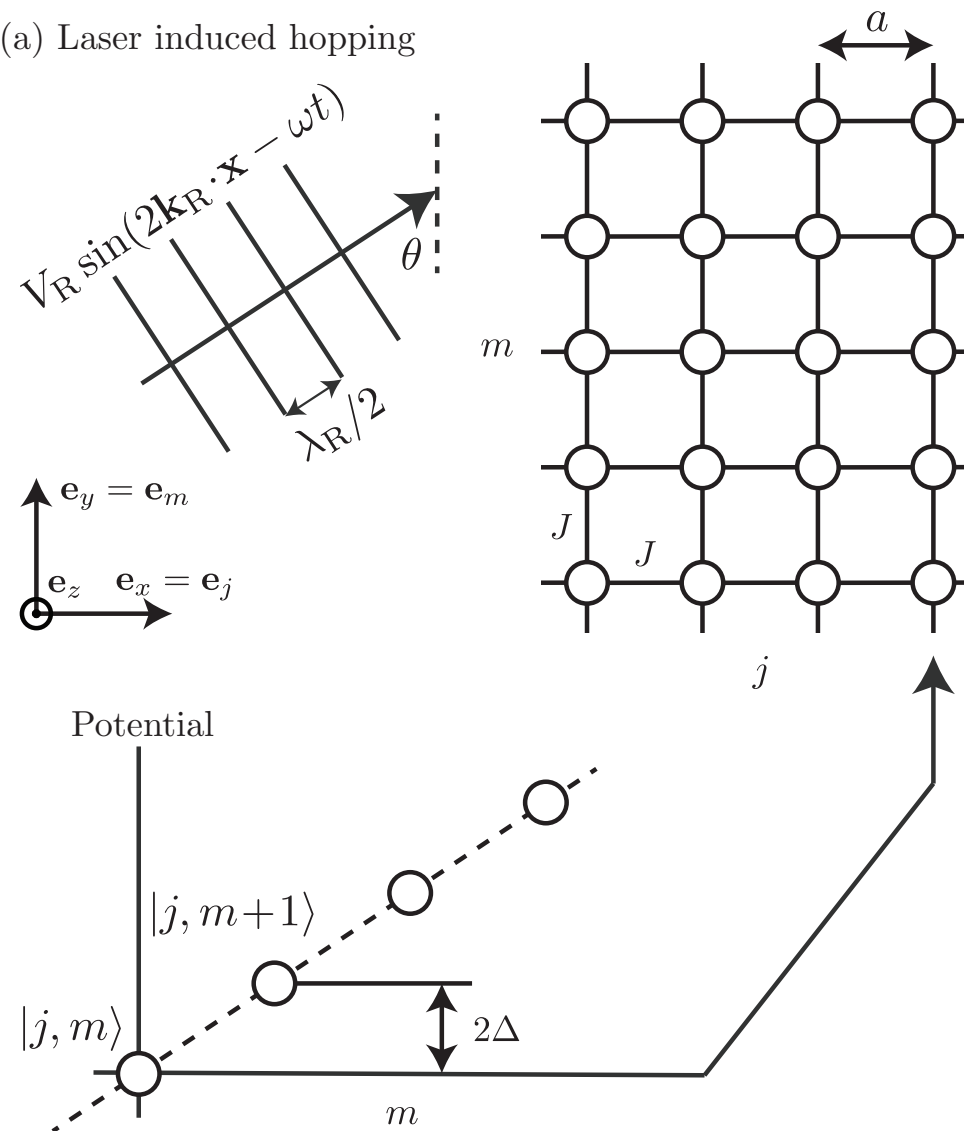
J. Gotzu *et al* Nature (2014)

# Backdrop

## Basic idea: laser induced hopping

$$H = - \sum_{\mathbf{j}} \left[ t^{(x)} e^{-i2\pi\Phi j_y} |\mathbf{j} + \mathbf{e}_x\rangle \langle \mathbf{j}| + t^{(y)} |\mathbf{j} + \mathbf{e}_y\rangle \langle \mathbf{j}| + \text{h.c.} \right]$$

(a) Laser induced hopping

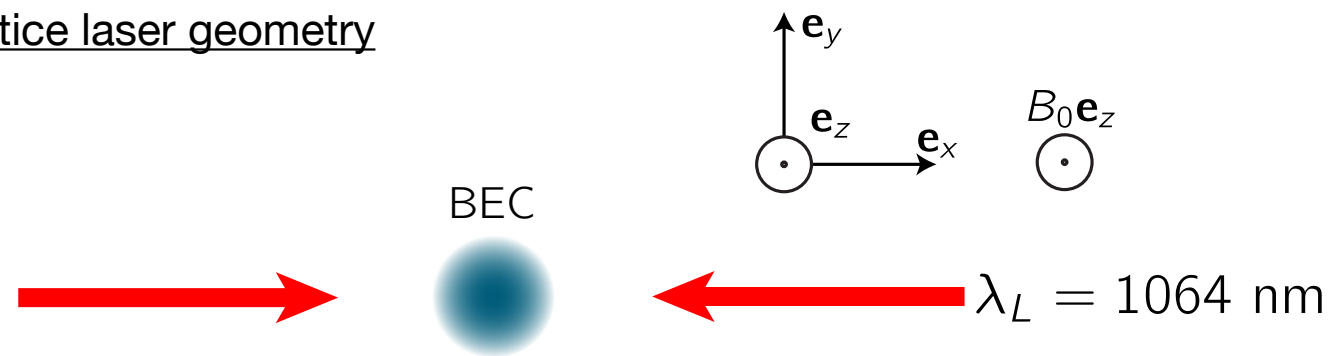


## References

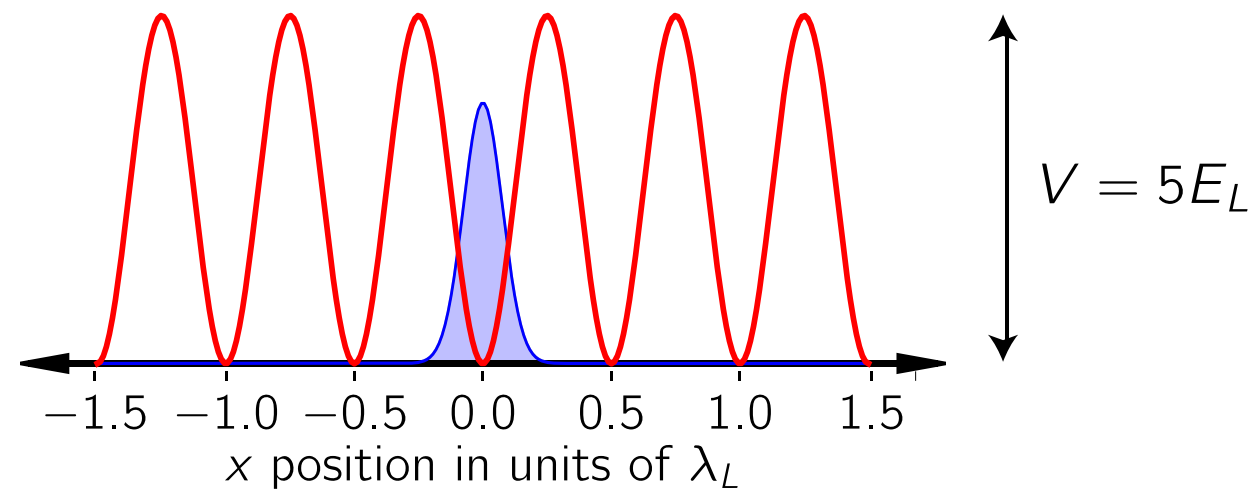
D. Jaksch and P. Zoller; New Journal of Physics (2003).

# Building a magnetic lattice

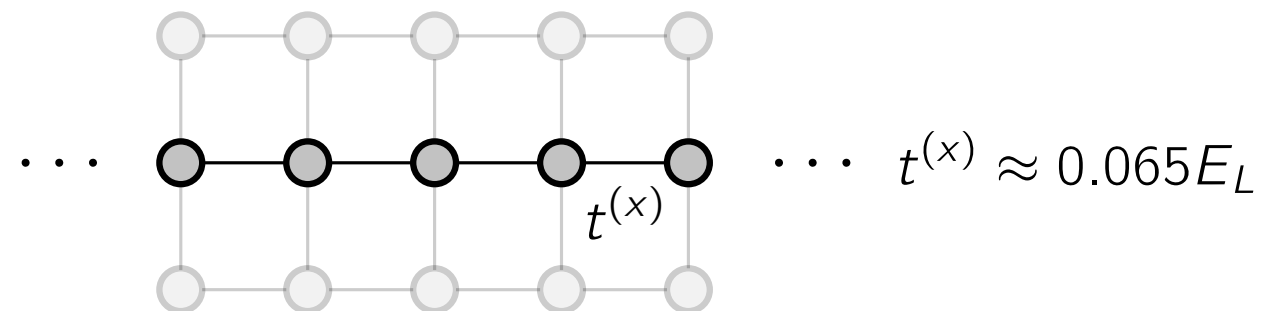
Lattice laser geometry



Lattice potential

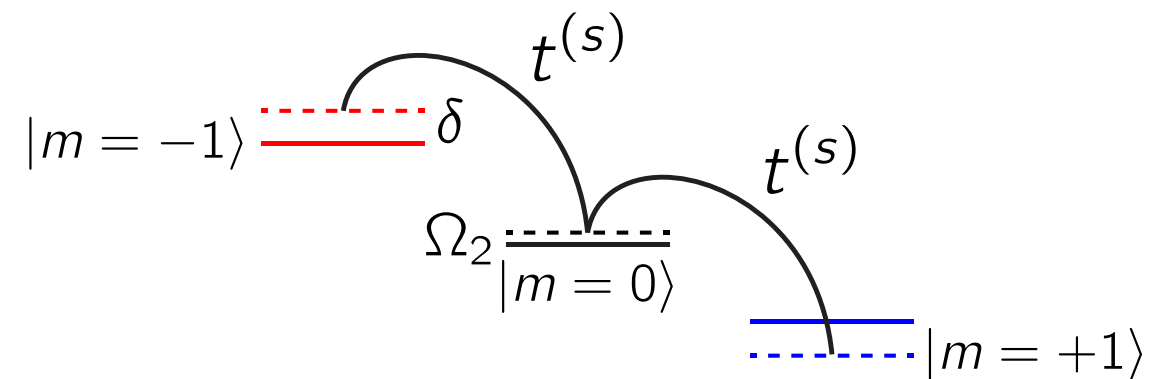


Tight binding model

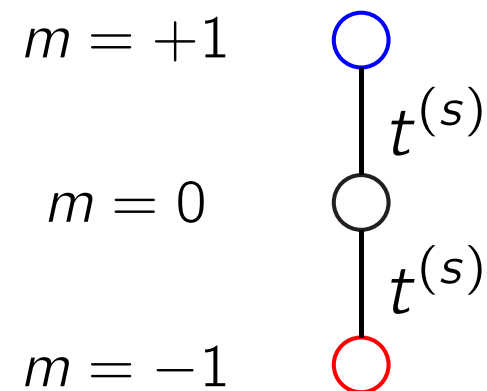


# Building a magnetic lattice

## Usual level diagram



## Lattice picture

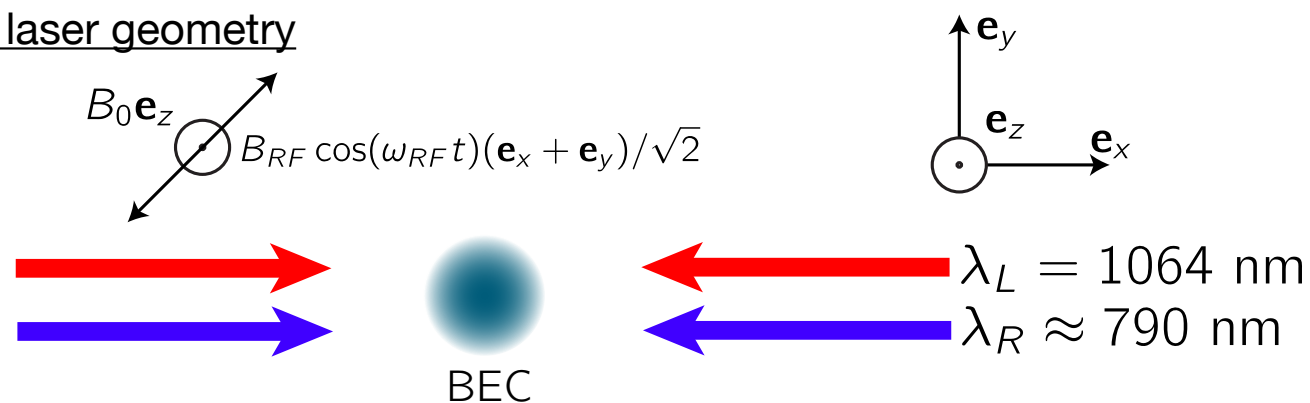


## Reference

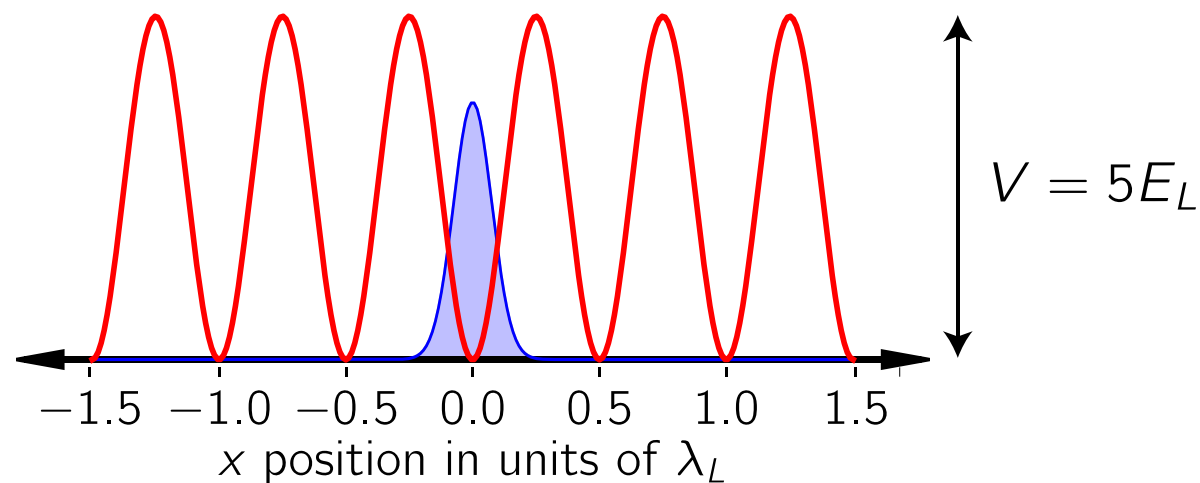
Celi, A. et al. Phys. Rev. Lett. (2014).

# All together: Full lattice

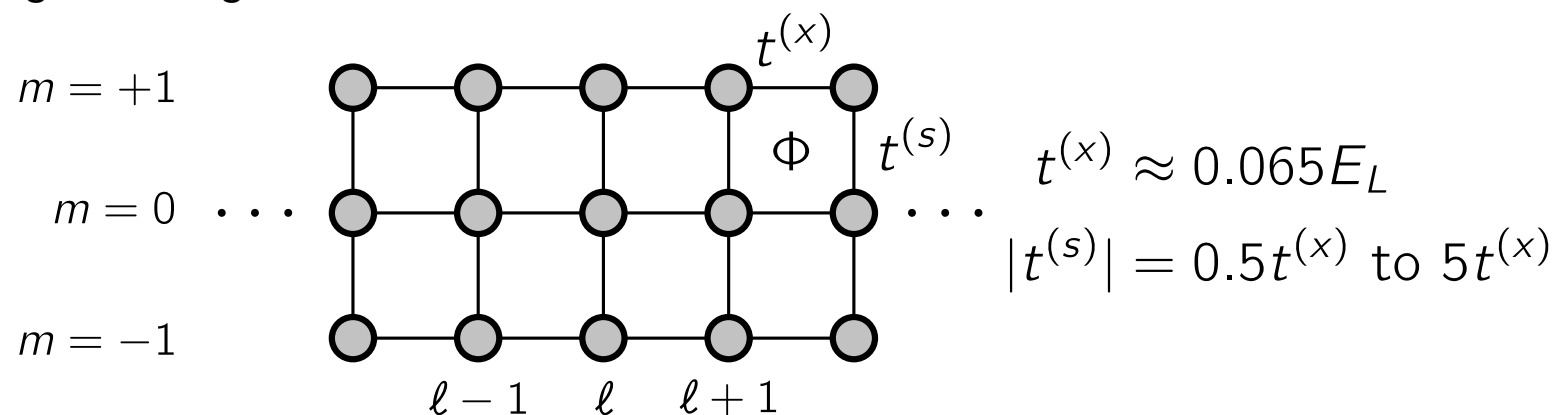
## Lattice laser geometry



## Lattice potential



## Tight binding model



## Synthetic hopping

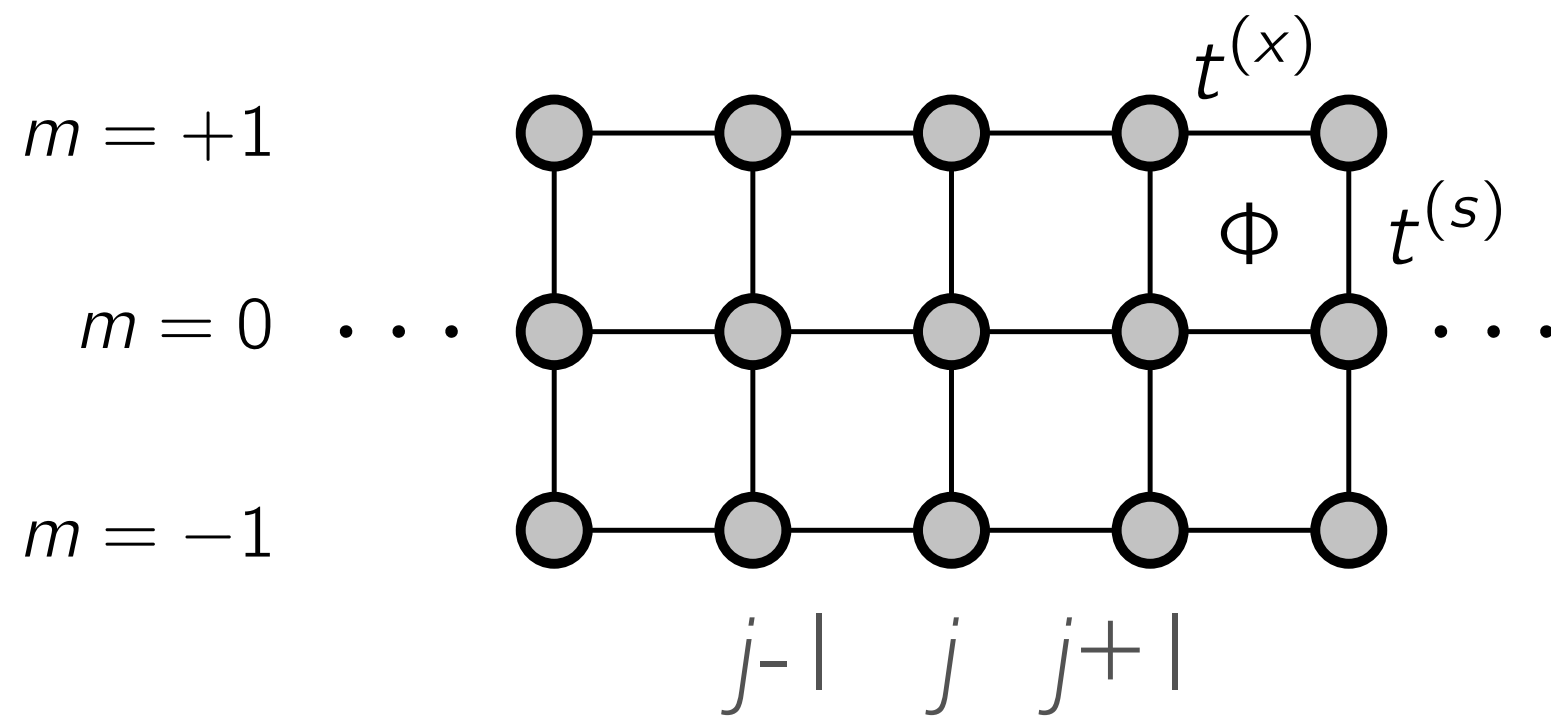
$$\begin{aligned}
 t^{(s)} &= \frac{\Omega_R}{\sqrt{2}} e^{i2k_R x} \\
 &= \frac{\Omega_R}{\sqrt{2}} e^{i(2\pi\Phi)\ell} \\
 \text{with } \Phi &= \frac{\lambda_L}{\lambda_R} \approx 1.32
 \end{aligned}$$

## References

Celi, A. et al. Phys. Rev. Lett. (2014); 3-site dual to: M. Atala et al. Nat. Phys. (2014)

# All together: Full lattice

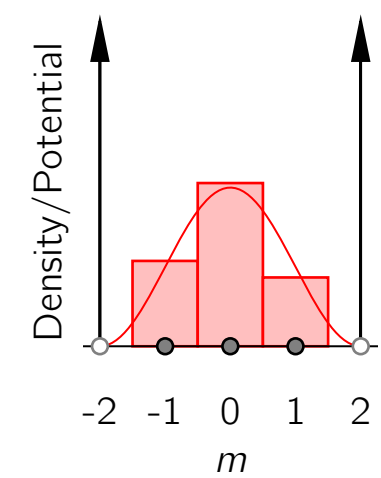
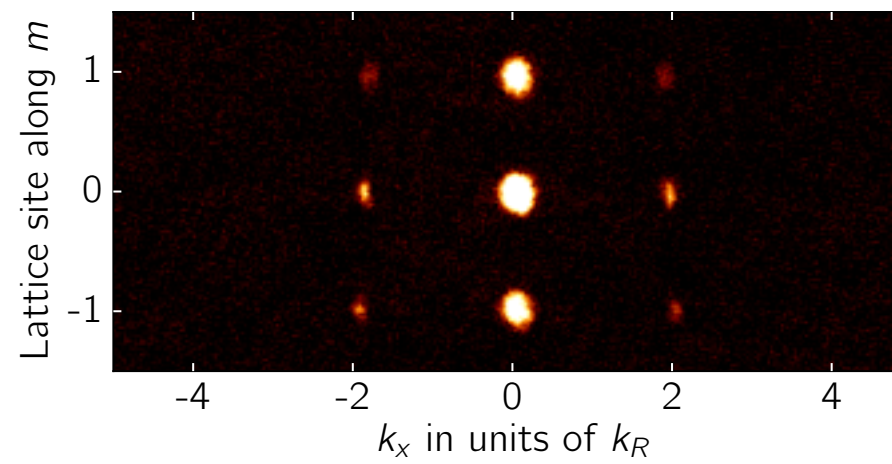
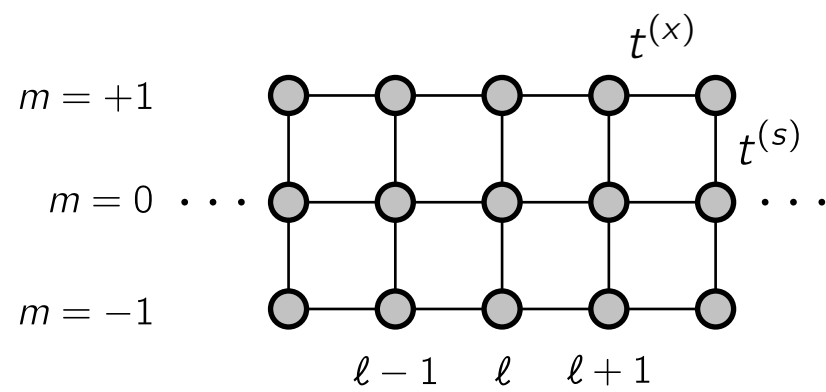
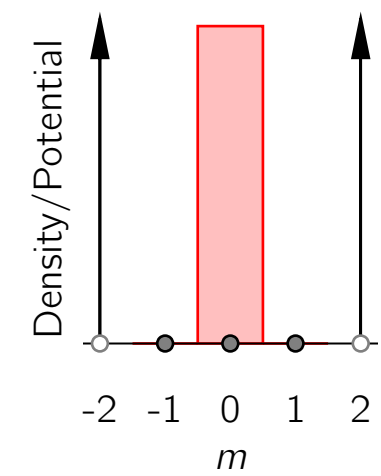
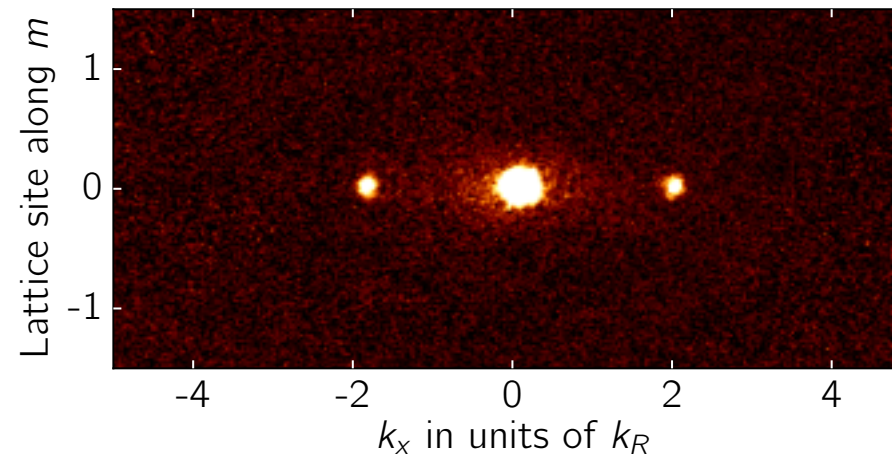
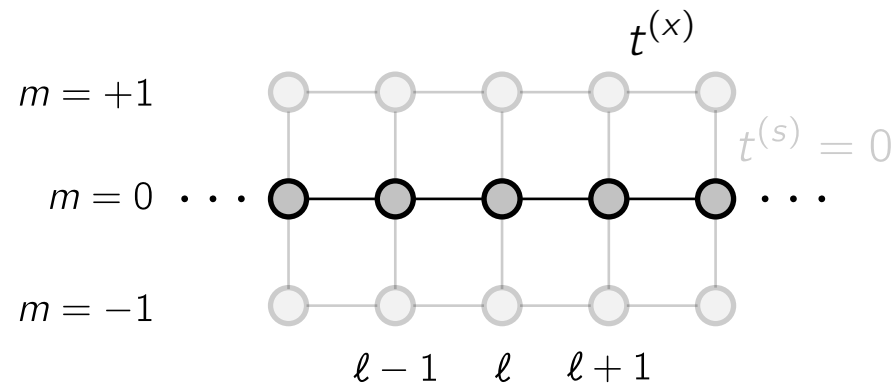
$$H = - \sum_{j,m} \left[ t_j |j+1, m\rangle \langle j, m| + t_s e^{i(\Phi j + \varphi)} |j, m+1\rangle \langle j, m| + \text{c.c.} \right]$$



## References

Celi, A. et al. Phys. Rev. Lett. (2014); 3-site dual to: M. Atala et al. Nat. Phys. (2014)

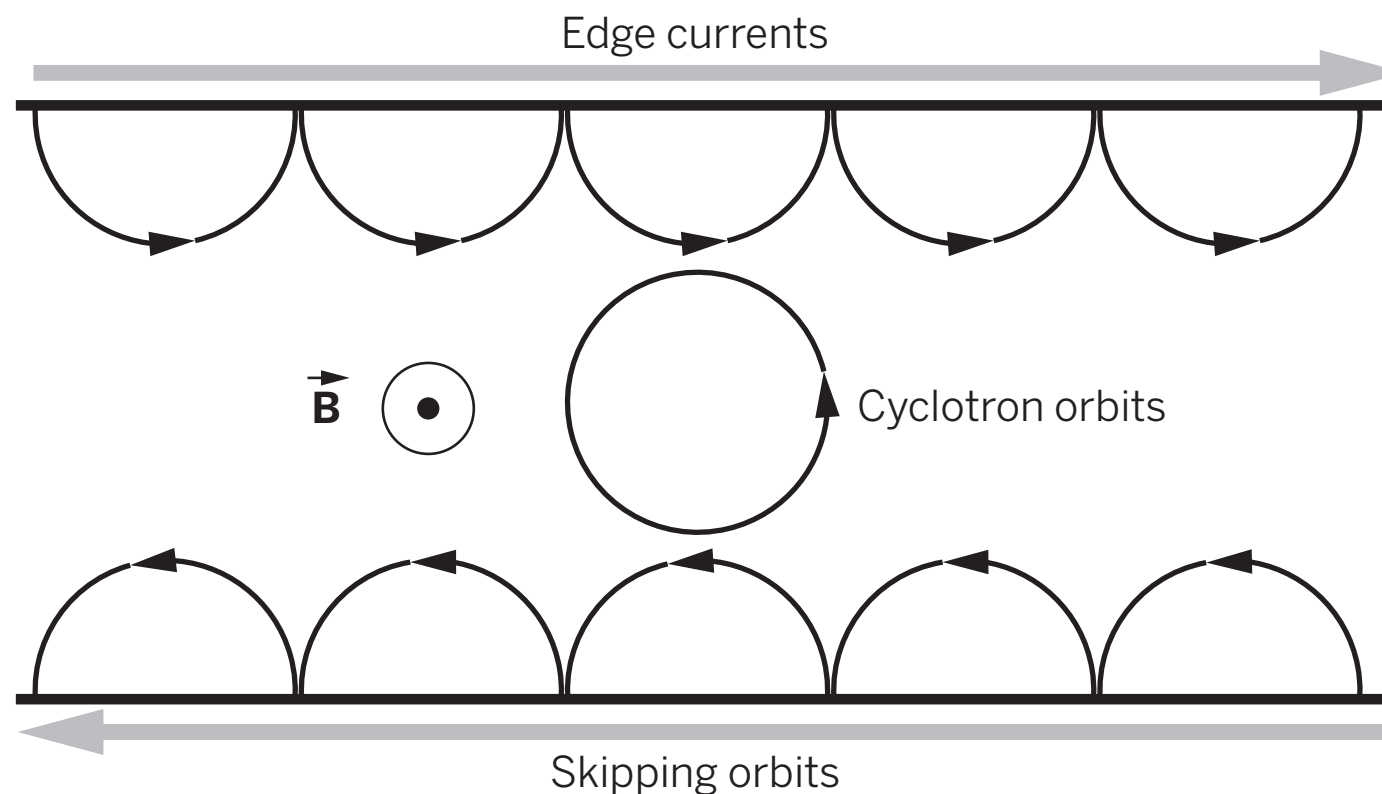
# Interpreting data



# Continuum magnetic fields

## Single-particle eigenstate structure: Landau gauge

$$H = \frac{\hbar^2}{2m} \left[ \left( k_x + \frac{qBy}{\hbar} \right)^2 + k_y^2 \right], \quad \text{from } \mathbf{A} = -By\mathbf{e}_x \quad \text{with} \quad \ell_B = \sqrt{\frac{\hbar}{qB}}$$



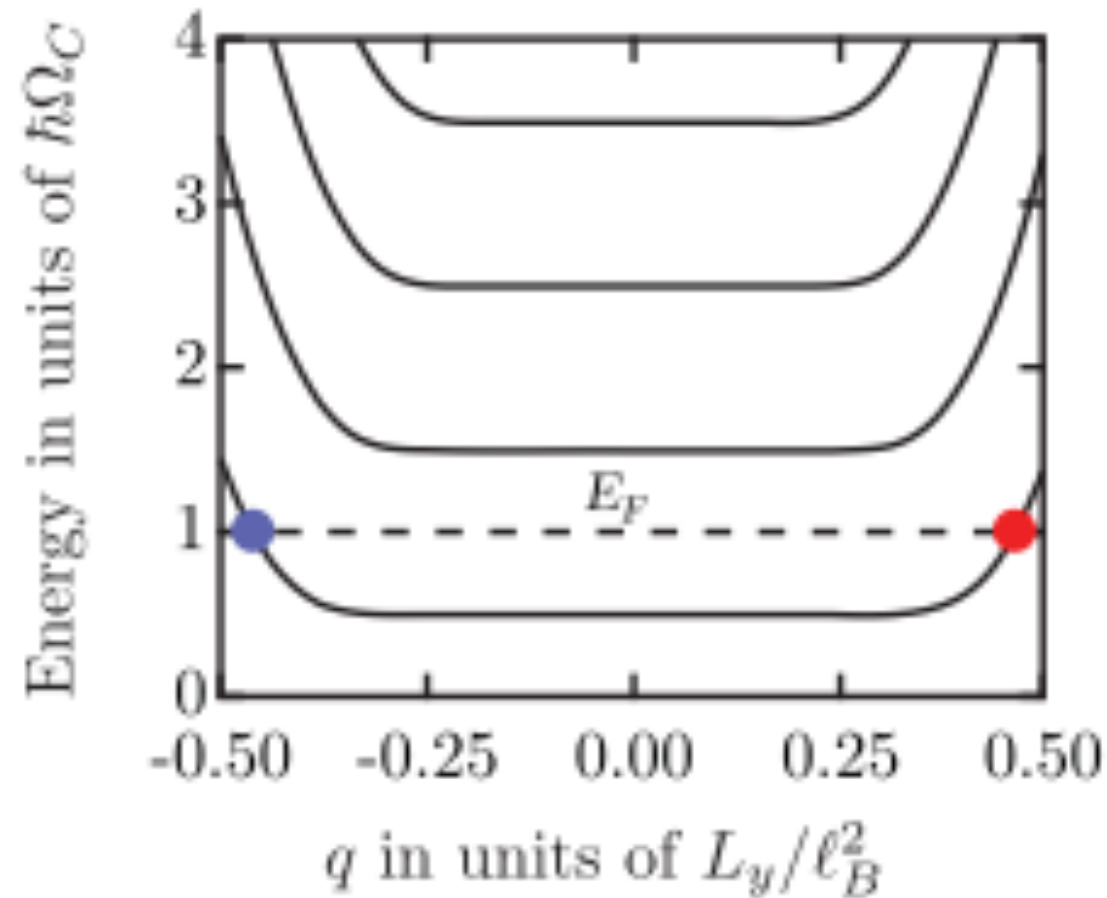
## References

Figure From: A. Cili and L. Tarruell, *Science Perspective* (2015)

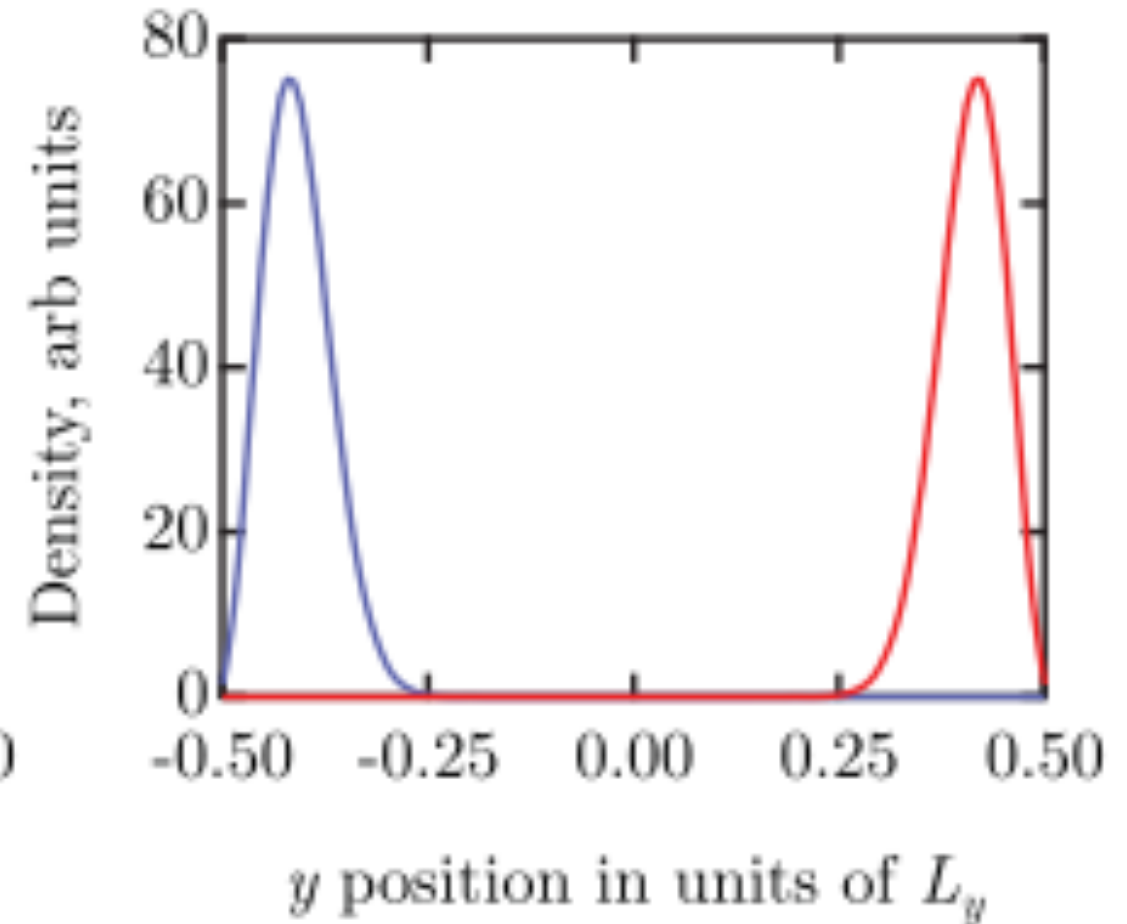
# QHE systems: Edge states

## Edge states in QHE systems

(a) Energies



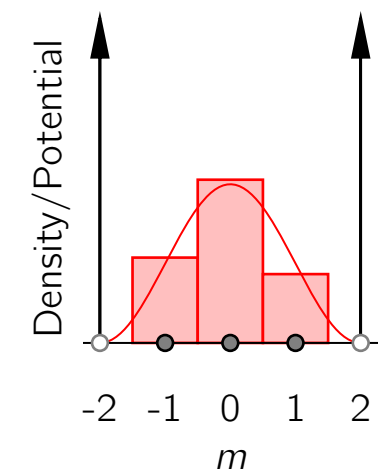
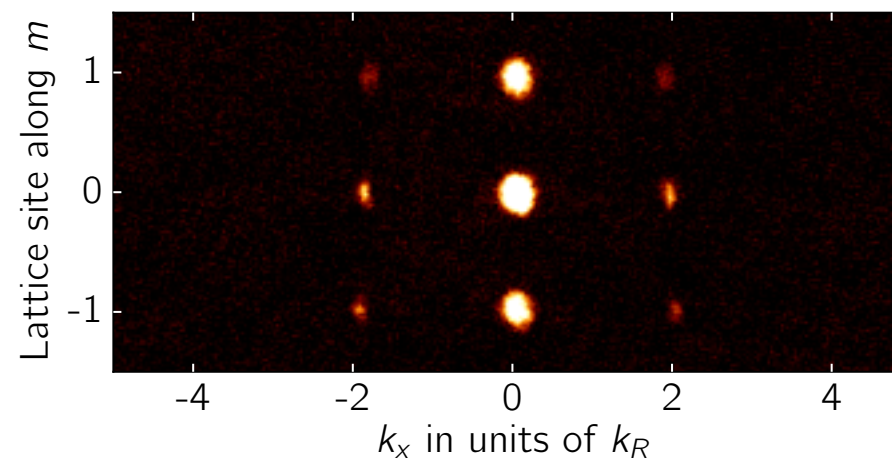
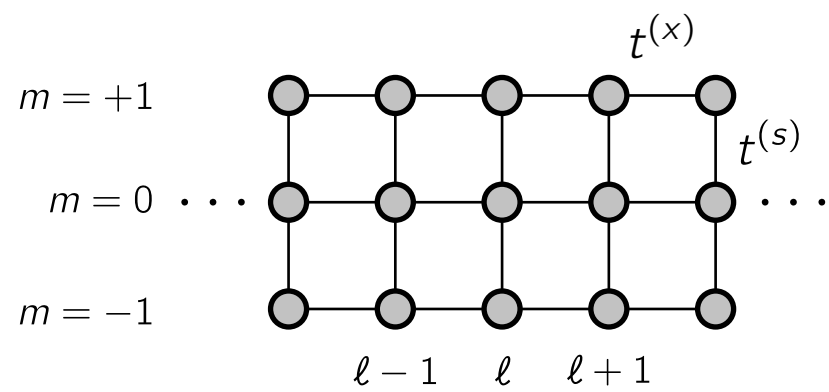
(b) Edge States



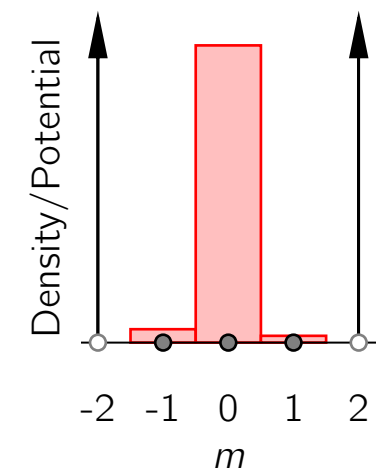
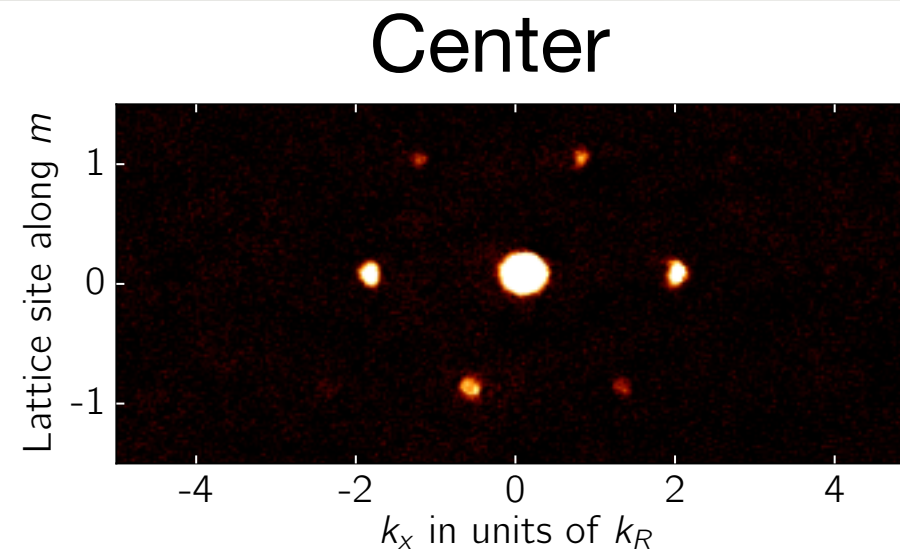
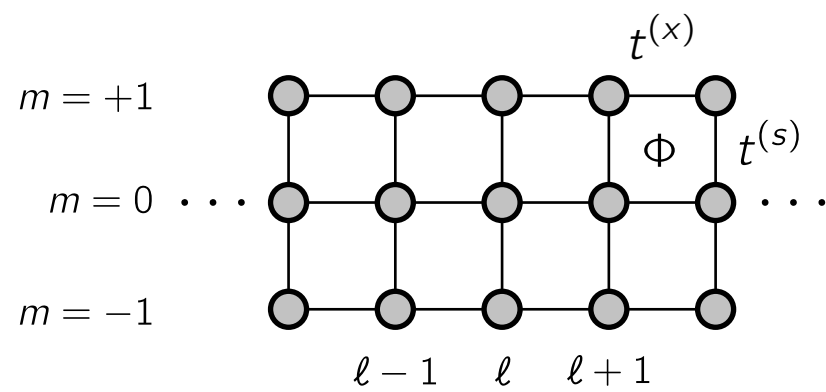
## References

I. B. Spielman Ann. der Phy. (2013).

# Interpreting data: zero flux

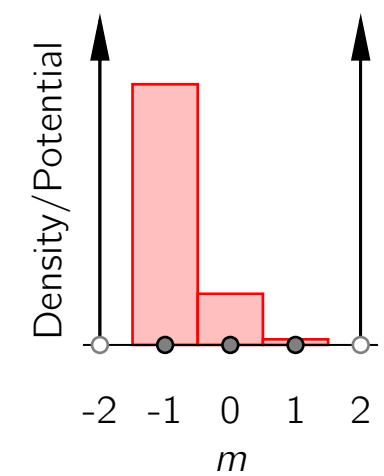
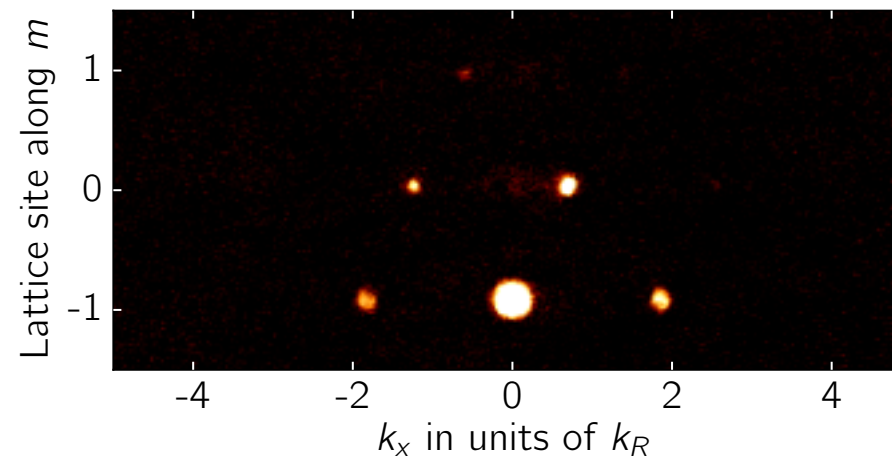
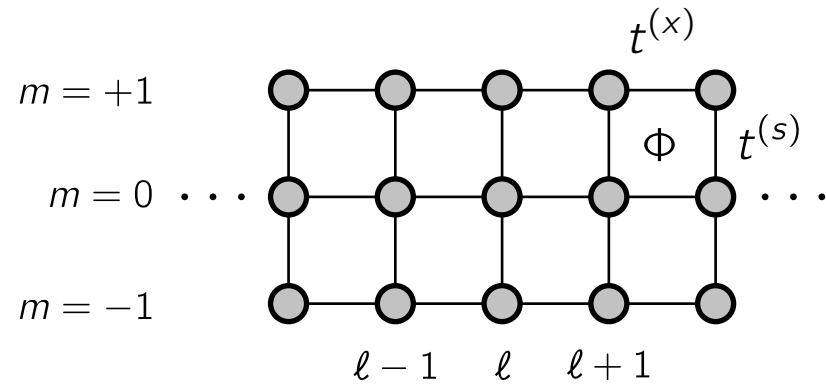


# Interpreting data: +1/3 flux quantum

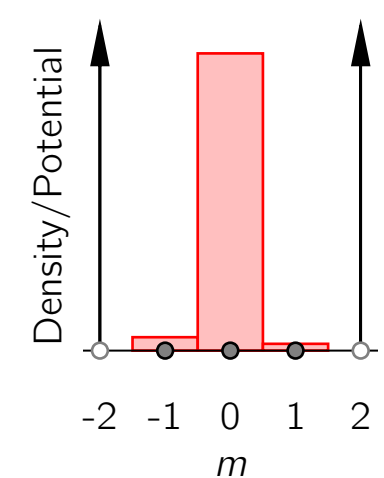
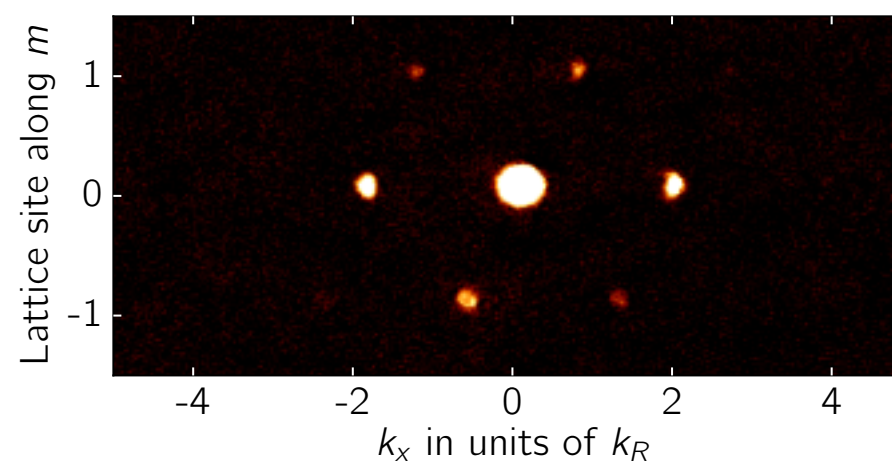
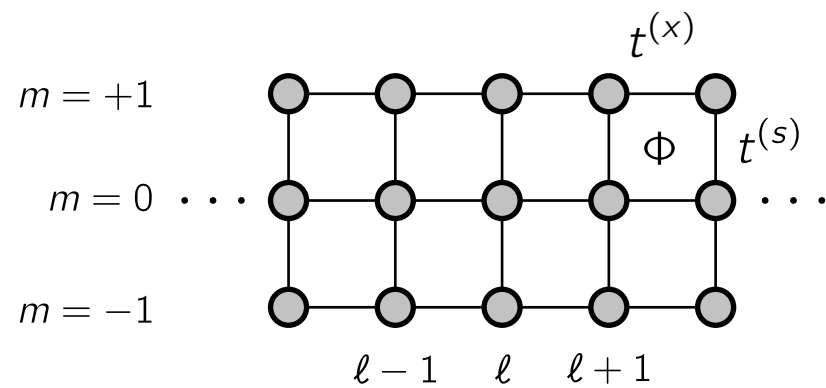


# Interpreting data: +1/3 flux quantum

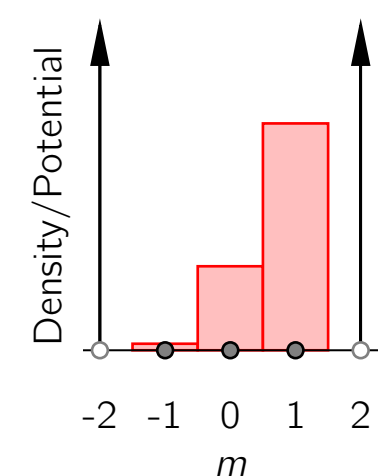
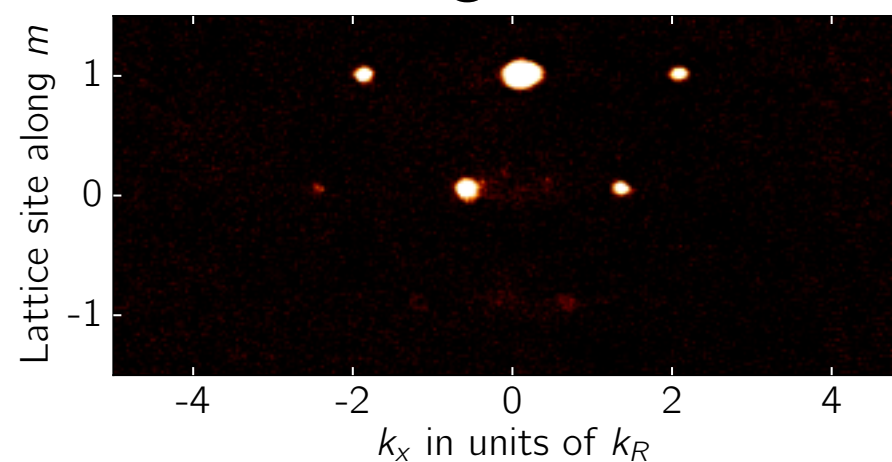
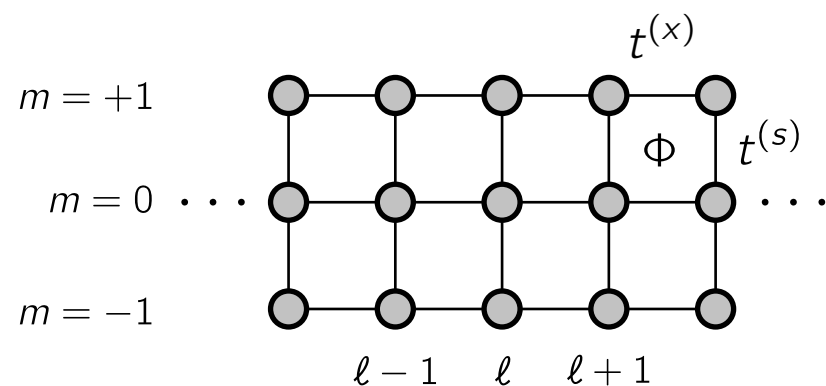
## -1 edge state



## Center

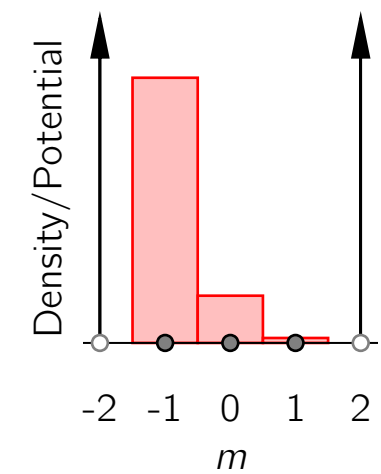
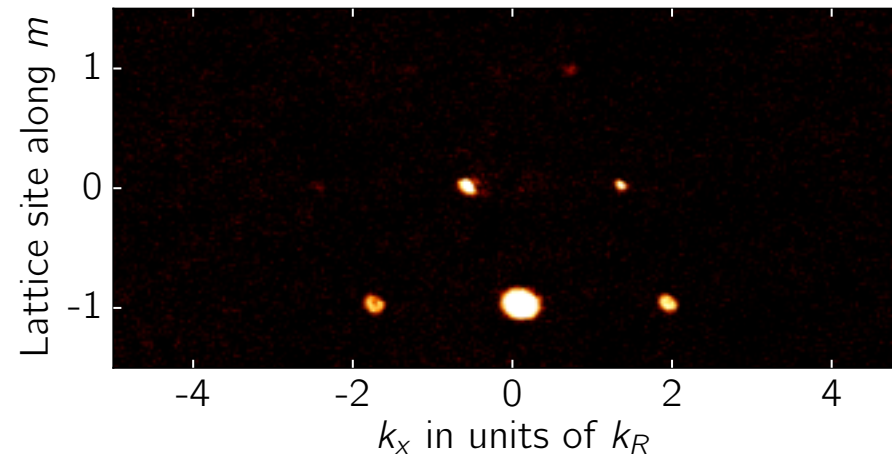
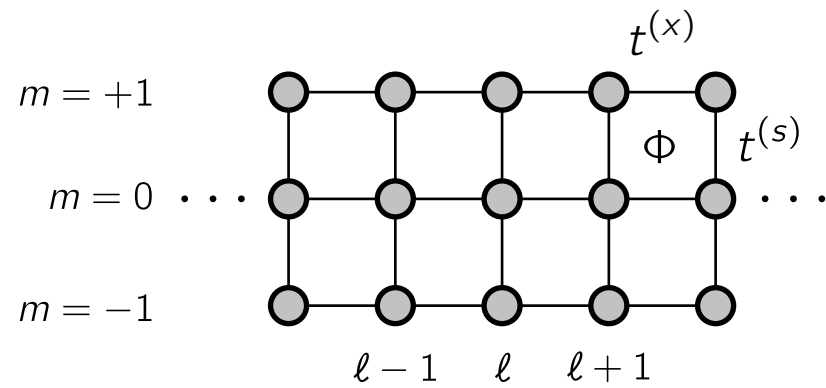


## +1 edge state

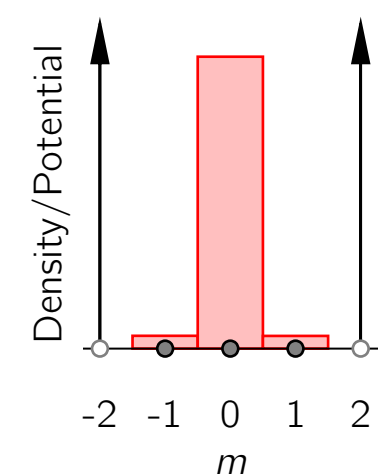
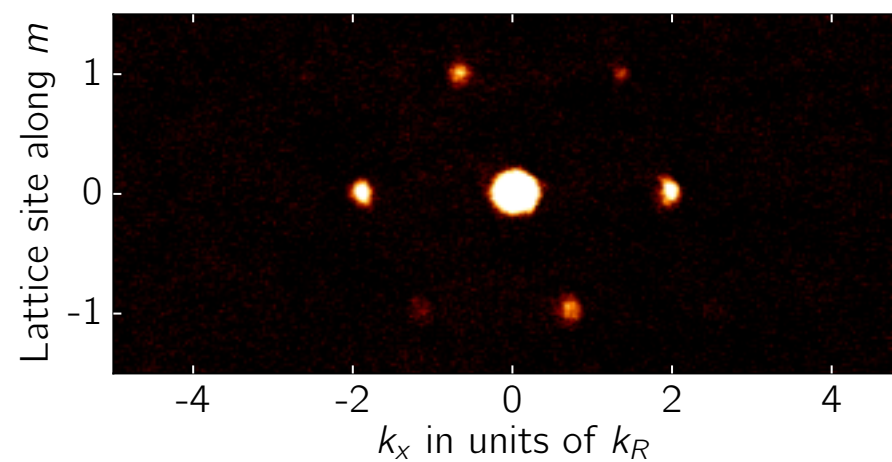
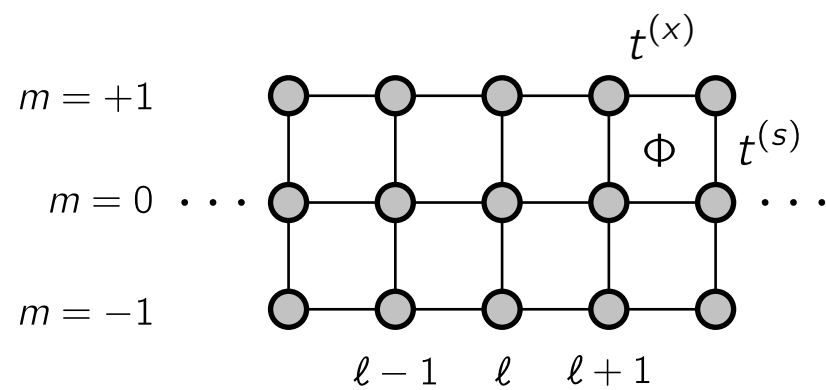


# Interpreting data: -1/3 flux quantum

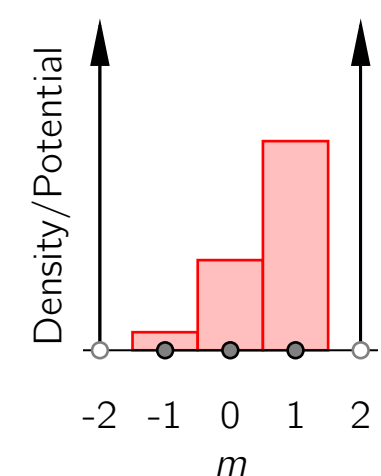
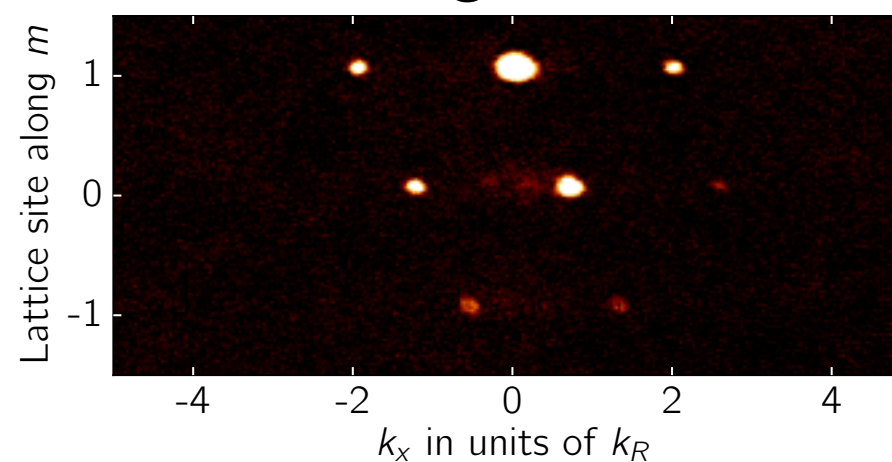
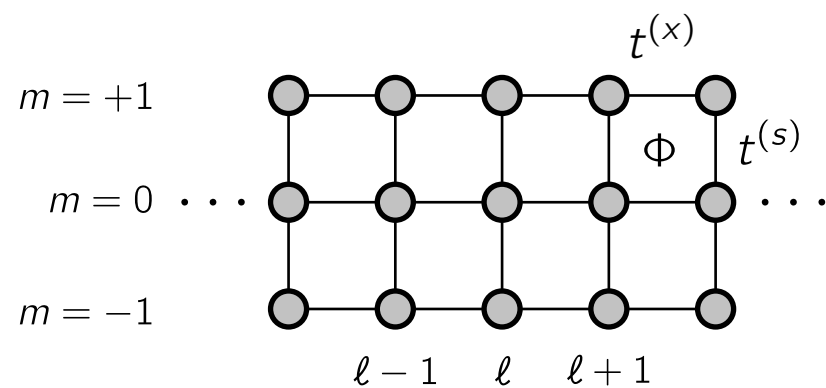
## -1 edge state



## Center

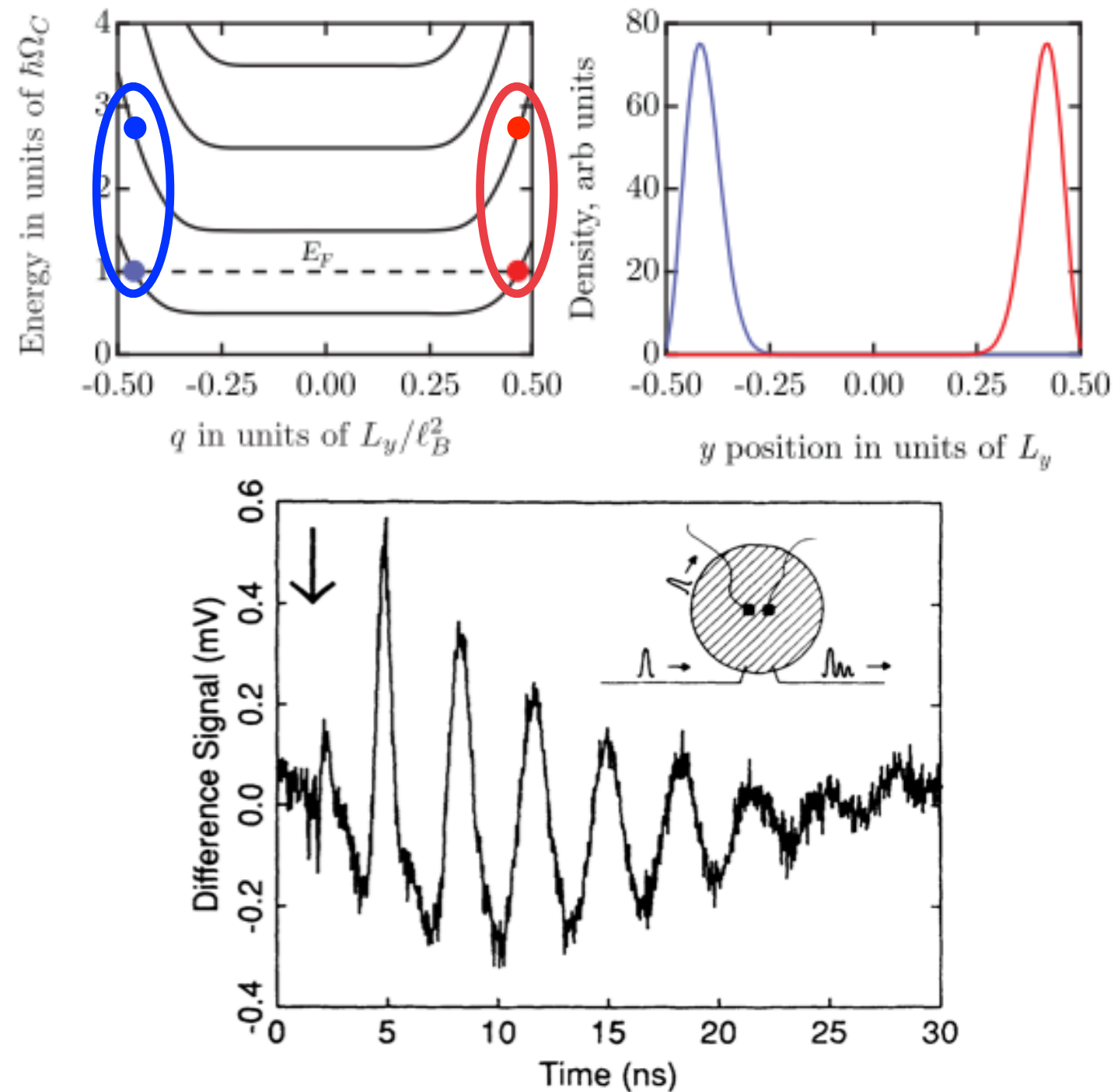


## +1 edge state



# QHE systems: edge states, skipping?

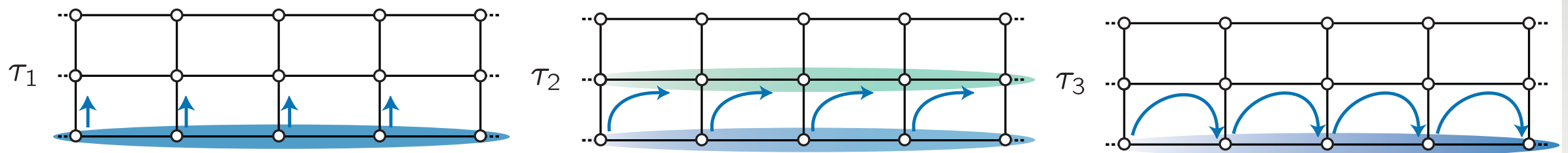
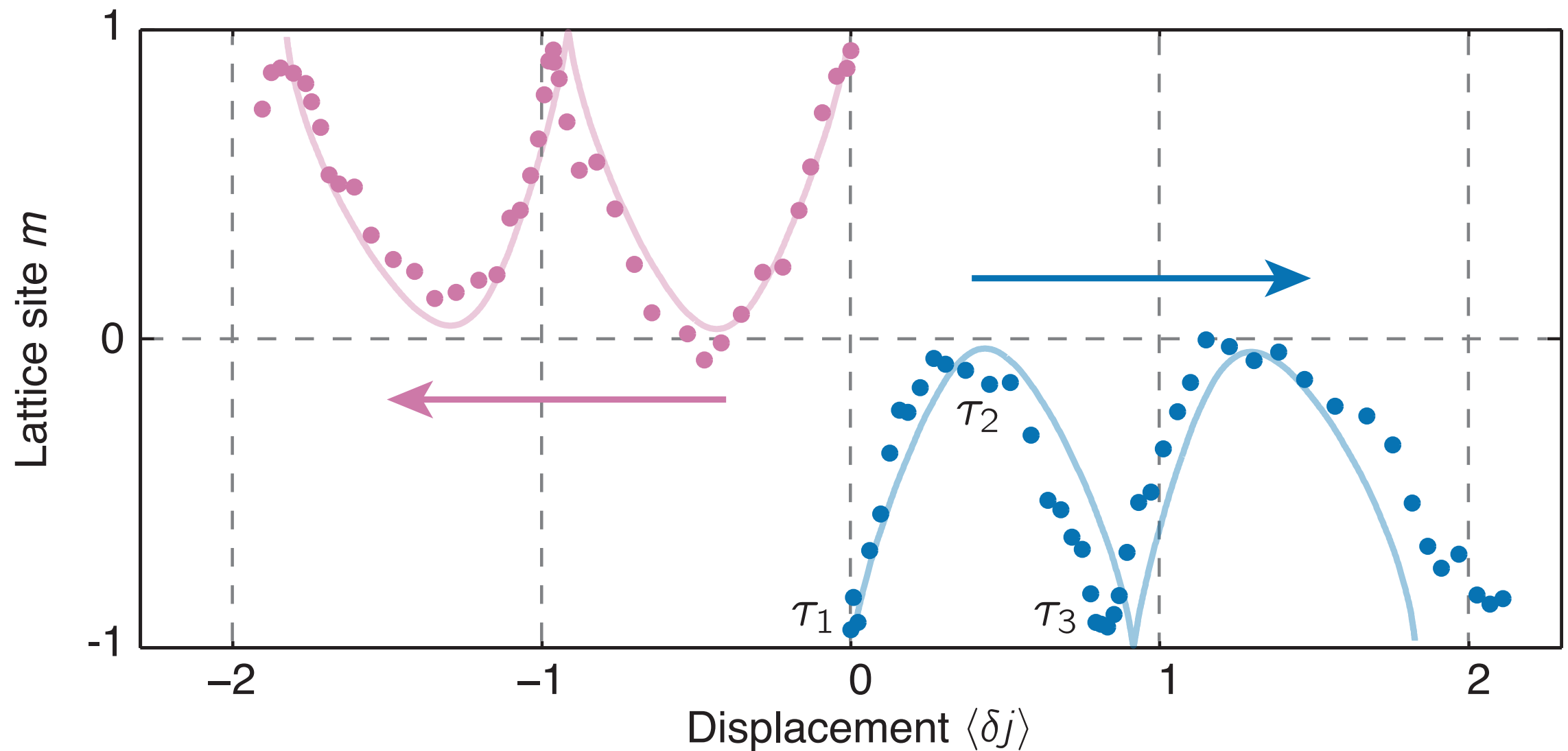
## Edge excitations in QHE systems



## References

R. Ashoori, et al., Phys. Rev. B 45, 3894–3897 (1992).

# Dynamics: edge magnetoplasmons

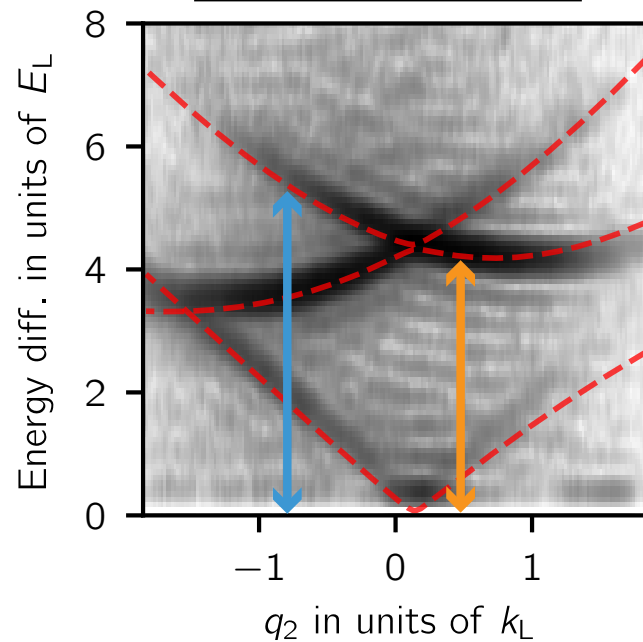


## References

B. Stuhl and H.-I Lu, et al., Science (2015); M. Mancini, et al., Science (2015)

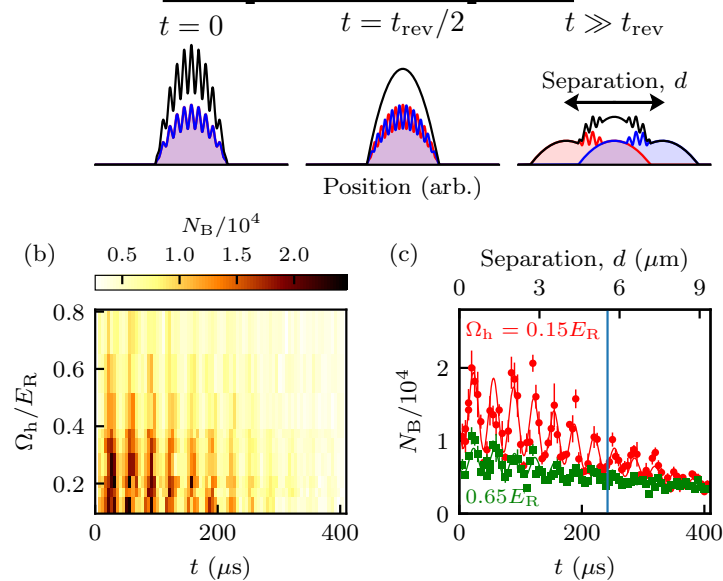
# Other recent work

## Rashba SOC



A. Valdés-Curiel et al Nat. Comm. (2021)

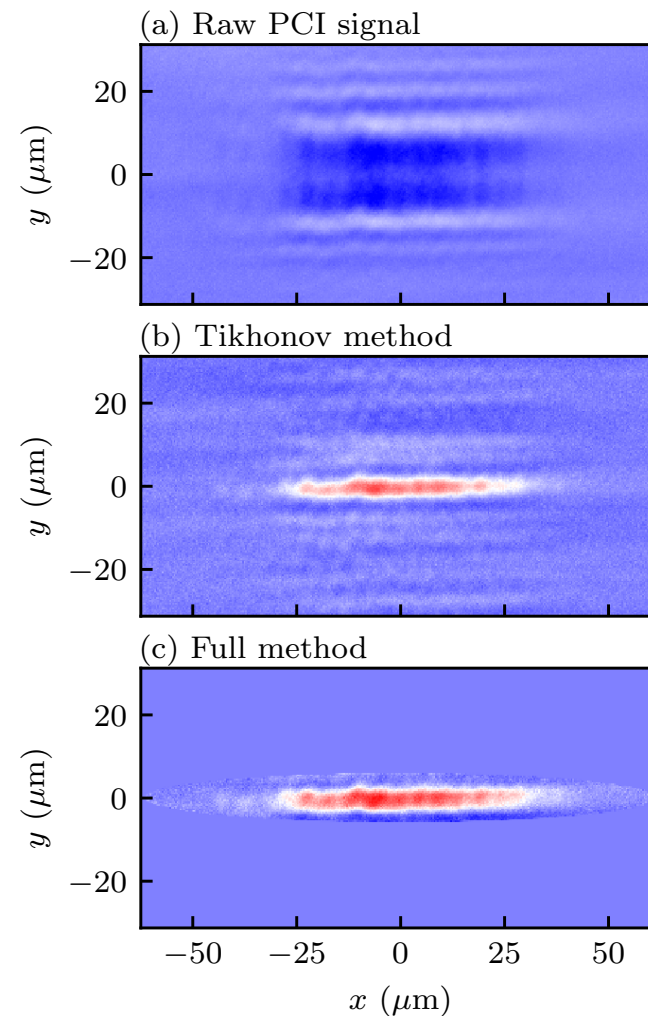
## Super-stripes



A. Putra et al.; PRL (2020)

## Fancy image processing

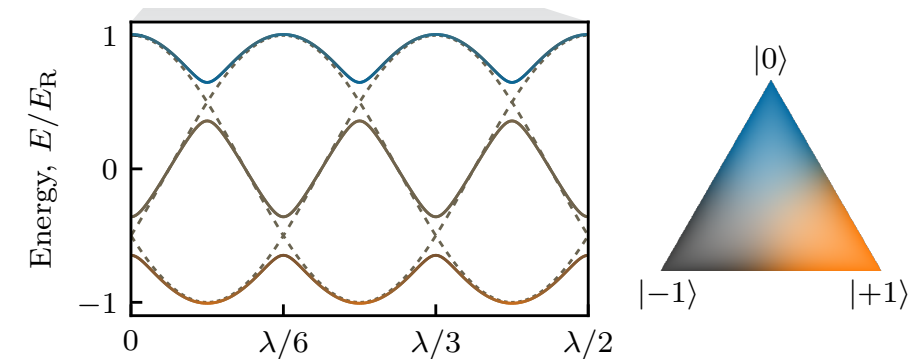
Recover images from imperfect data



E. Altuntas and IBS  
(2021 in preparation)

## Sub-wavelength lattice

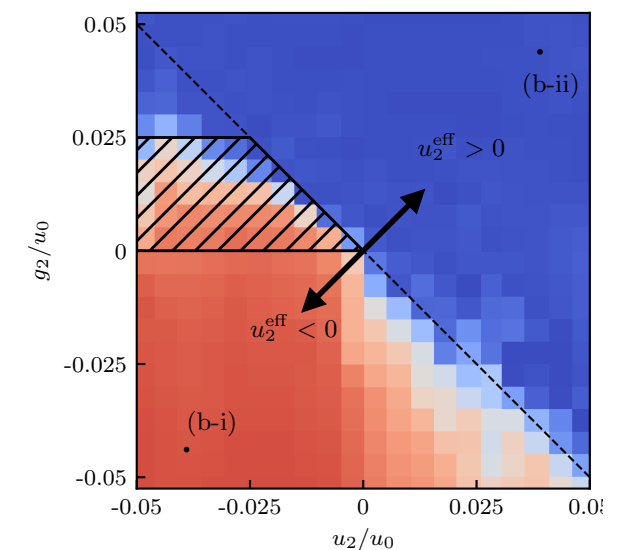
Ring coupling w/o added lattice



R. Anderson et al  
PR Research (2020)

## Theory: effective interactions

Weak measurement + classical  
feedback in spinor systems



H. M. Hurst, and IBS; PRR (2020)